THOMPSON, ROGER JOHN

THE DESIGN AND MANAGEMENT OF SURFACE MINE HAUL ROADS

PhD UP 1996

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THE DESIGN AND MANAGEMENT OF SURFACE MINE HAUL ROADS

Roger John Thompson

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ABSTRACT

Title:	**The design and management of surface mine haul roads**
Author:	**Roger John Thompson**
Supervisor:	**Professor A T Visser**
Degree:	**Philosophiae Doctor (Engineering)**
Department:	**Civil Engineering**

Unpaved mine haul roads provide the principal means of material transport on surface strip coal mines. Design and management of these roads was based primarily on local experience and adopted empirical guidelines. With the trend in increasing truck size, these current pavement design and management systems proved inadequate. Not only would the maintenance costs of existing roads increase, vehicle operating and maintenance costs would also increase prohibitively.

The primary objective of this research was the development of a practical total haul road design and management methodology that encompasses pavement strength, wearing course functionality and road maintenance scheduling and management components. A revised mechanistically derived optimal structural design is presented together with design criteria and recommended effective elastic modulus values for typical construction materials. The placement of those materials as pavement layers was analysed, such as to optimise their performance both as individual layers and over the entire structure.

The development and analysis of suitable material selection guidelines for use in haul road functional design was allied to the development of a qualitative defect assessment and ranking methodology. A revised range of material selection parameters was derived based on road-user acceptability criteria and actual material defect rankings. By analysing the trends evident in the individual defect rankings, the predictive capability of the specification was enhanced by depicting the typical functional defects arising when departures are made from the recommended material parameter limits.

Maintenance design concerns the optimal frequency of wearing course maintenance commensurate with minimum vehicle operating and road maintenance costs. A qualitative road roughness evaluation technique was developed as a precursor to the development of a model for roughness progression. Expressions were developed to enable direct comparison to be made between qualitatively derived roughness and International Roughness Index (IRI). Models of vehicle operating and road maintenance cost variation with road roughness were combined with roughness progression models to determine the optimal maintenance strategy.

Through an analysis of the current expenditure on mine haul road construction and operation, the adoption of these revised and improved haul road design methodologies have been shown to be associated with potentially significant cost savings and improvements in the structural, functional and maintenance management aspects of haul road design.

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SUMMARY

THE DESIGN AND MANAGEMENT OF SURFACE MINE HAUL ROADS

Roger John Thompson

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

Unpaved mine haul roads provide the principal means of material transport on surface strip coal mines. With the expansion of surface mining in South Africa and in particular coal strip mining, the use of ultra-heavy off-highway trucks, currently capable of hauling payloads in excess of 160t, has become commonplace. Design and management of these roads was based primarily on local experience and adopted empirical guidelines. 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 road maintenance costs and vehicle maintenance costs. As the trend in increasing truck size continues, these current pavement design and management systems proved inadequate. Not only would the maintenance costs of existing roads increase, vehicle operating and maintenance costs would also increase prohibitively.

The primary objective of this research was the development of a portable and practical total haul road design and management methodology that encompasses both pavement strength, wearing course functionality and road maintenance management components. The structural design concerns the ability of a haul road to carry the imposed loads without the need for excessive maintenance. A revised mechanistically derived structural design is presented together with the associated limiting design criteria and recommended target effective elastic modulus values for the construction materials available. The placement of those materials as pavement layers, such as to optimise their performance both as individual layers and over the entire structure is analysed.

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. The development and analysis of suitable material selection guidelines for use in haul road functional design was allied to the development of a qualitative defect assessment and ranking methodology in order to assess the utility of established performance related selection guidelines and as a basis for revised functional performance parameter specification. A revised range of parameters was derived based on road-user acceptability criteria. By analysing the trends evident in the individual defect rankings, the predictive capability of the specification was enhanced by depicting the typical functional defects arising when departures are made from the recommended material property limits.

Maintenance design concerns the optimal frequency of wearing course maintenance commensurate with minimum vehicle operating and road maintenance costs. A qualitative road roughness evaluation technique was developed as a precursor to the development of a model for roughness progression. Expressions were developed to enable direct comparison to be made between the qualitative roughness defect score and International Roughness Index (IRI). The second element of a maintenance management system was based on models of the variation of vehicle operating and road maintenance costs with a road roughness model. The combination of these models enabled the optimal maintenance strategy to be sought based on the minimisation of these costs. Sub-optimal maintenance strategies were seen to be associated with unwarranted expenditure on total road-user costs.

This thesis makes a contribution to the state of knowledge through the development and synthesis of structural, functional and maintenance management aspects of haul road design. The adoption of these revised and improved haul road design methodologies are associated with potentially significant cost savings and operational improvements.

Keywords
Surface mine, road, design, structural, mechanistic, functional, maintenance, wearing course, hauling, transport.

SAMEVATTING

DIE ONTWERP EN BESTUUR VAN MYNVERVOERPAAIE

Roger John Thompson

Promoter: Professor A T Visser

Departement: Siviele Ingenieurswese

Universiteit: Universiteit van Pretoria

Graad: Philosophiae Doctor (Ingenieurswese)

Ongeplaveide mynvervoerpaaie voorsien die primêre vervoer metode van materiaal in steenkoolstrookdagmyne. Met die uitbreiding van dagmynbou in Suid-Afrika en in besonder in die steenkoolstrookmynbou, het die gebruik van swaar vervoertrokke alledaags geword. Ontwerp en bestuur van hierdie paaie was hoofsaaklik gebaseer op plaaslike ondervinding en empiriese riglyne. Hierdie ontwerp metode het sy doel gedien in 'n tydperk waarin die trokke ligter en 'n kleiner finansiële uitleg nodig was, beide in terme van inisiële plaveisel konstruksie kostes en voortdurende padonderhoudskostes en voertuig instanthoudingkostes. Soos wat die tendens van toename in trokgrootte voortduur, sal die huidige plaveisel ontwerp en bestuursstelsels onvoldoende wees. Nie alleen sal die ondershoudskostes van bestaande paaie verhoog nie, maar voertuigbedryf en -instandhoudingkostes sal buitensporig word.

Die primêre doel van die navorsing was die ontwikkeling van 'n oordraagbare en praktiese totale vervoerpadontwerp en bestuursmetodiek wat die plaveiselsterkte, slytlaag funksionele werkverrigting en padonderhoudbestuur komponente insluit. Die strukturele ontwerp behels die vermoë van 'n vervoerpad om die toegepaste las te kan dra sonder die noodsaaklikheid van buitensporige onderhoud. 'n Hersiene meganisties strukturele ontwerp word aangebied tesame met die geassosieerde ontwerpkriterium en aanbevole effektiewe elastisiteitsmoduluswaardes vir die beskikbare konstruksie materiaal. Die plasing van daardie materiale as plaveisellae, om sodanig hulle werkverrigting te optimeer is, as beide individuele lae en oor die hele struktuur, geanaliseer.

verrig, naamlik om 'n ekonomiese, veilige en voertuigvriendelike rit te voorsien. Die ontwikkeling en analise van geskikte materiaal seleksie is gekoppel aan die ontwikkeling van 'n kwalitatiewe defek waardebepaling en ranglys metodiek om die bruikbaarheid van vasgestelde prestasie-verwante seleksie riglyne te kan bepaal en as basis vir hersiene funksionele prestasie parameter spesifikasies. 'n Hersiene reeks parameters is afgelei, gebaseer op padverbruiker aanvaarbaarheids kriterium. Deur analise van die tendens in die individuele defek ranglys, is die voorspelbaarheids vermoë van die spesifikasies verhoog deur die uitwysing van tipiese funksionele defekte wat voorkom wanneer afgewyk word van aanbevole materiaal parameter beperkings.

Die onderhoud aspek van vervoerpad ontwerp kan nie afsonderlik van die strukturele en funksionele ontwerp aspekte oorweeg word nie. Onderhoudontwerp behels die optimale frekwensie van slytlaag onderhoud eweredig aan die minimum voertuigbedryf en padonderhoudskostes. 'n Kwalitatiewe pad ongelykheid evaluasie tegniek is ontwikkel as 'n voorloper tot die ontwikkeling van 'n ongelykheid progressie model. Uitdrukkings is ontwikkel om direkte vergelyking tussen ongelykheid defektelling en Internasionale ongelykheids indeks (IRI) moontlik te maak. Die tweede element van 'n onderhouds bestuurstelsel is gebaseer op modele van die variasie van die voertuigbedryf en instandhoudingkoste en padongelykheid. Die kombinasie van hierdie modelle stel die verbruiker in staat om die optimale onderhoudstrategie te soek. 'n Sub-optimale padonderhouds strategië was geassosieer met buitensporige besteding op totale padverbruikers koste.

Hierdie proefskrif lewer 'n bydrae tot die staat van kennis deur die ontwikkeling en samevoeging van die strukturele, funksionele en onderhoud bestuurs aspekte van mynvervoerpadontwerp. Die ingebruikneming van die hersiene en verbeterde vervoerpad ontwerp en bestuur metodiek het die potensiaal om beduidende koste besparings te verwesenlik.

Sleutelwoorde

Dagmyn, mynvervoerpad, plaveiselontwerp, strukturele, meganisties, funksionele, padonderhoud, sluitlaag, vervoertrok, vervoer.

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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.

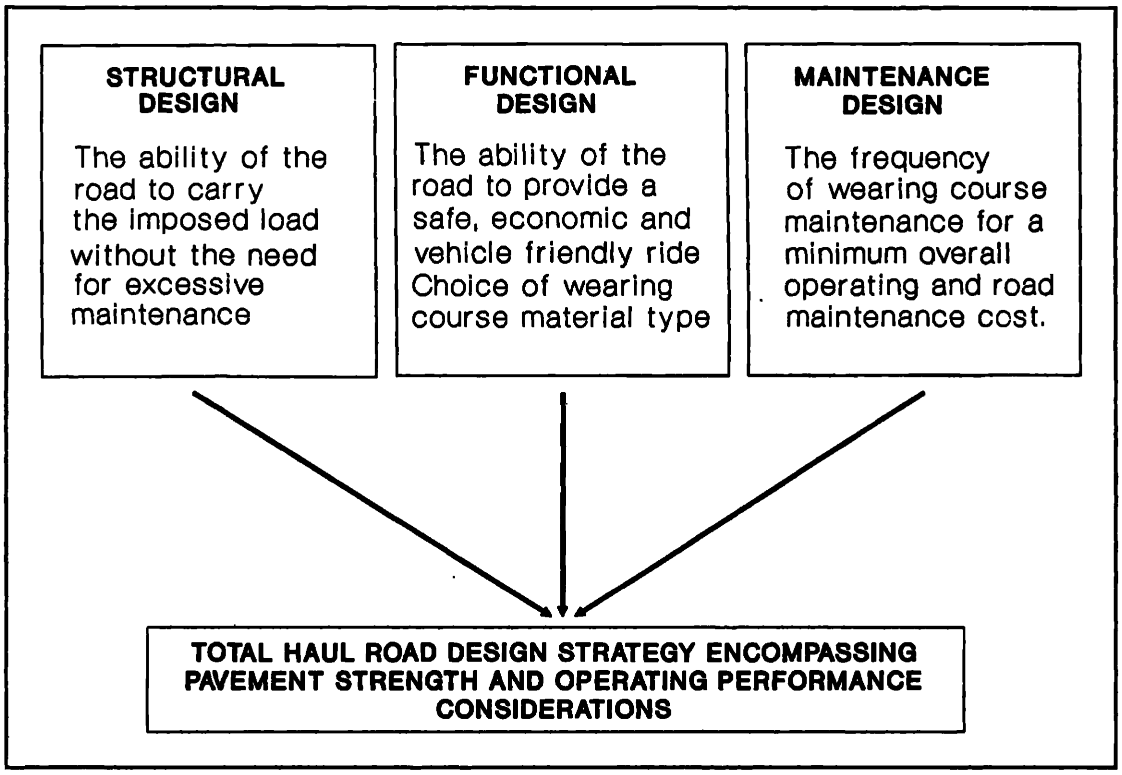


Figure 1.1 Elements of a Total Haul Road Design Strategy.

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.

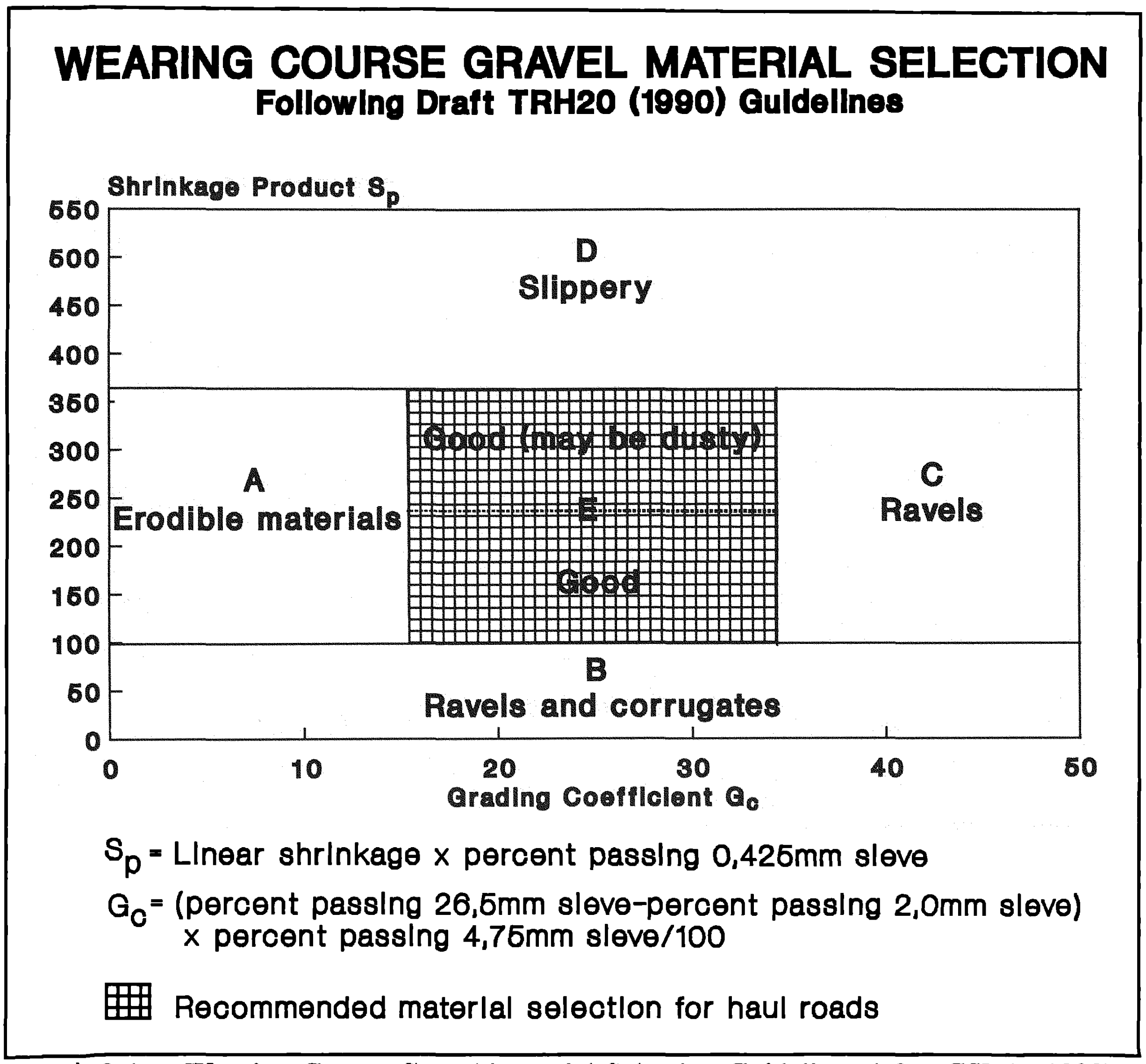


Figure 2.1 Wearing Course Gravel Material Selection Guidelines (after CSRA, 1990)

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

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.

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 are based on the optimisation of these elements.

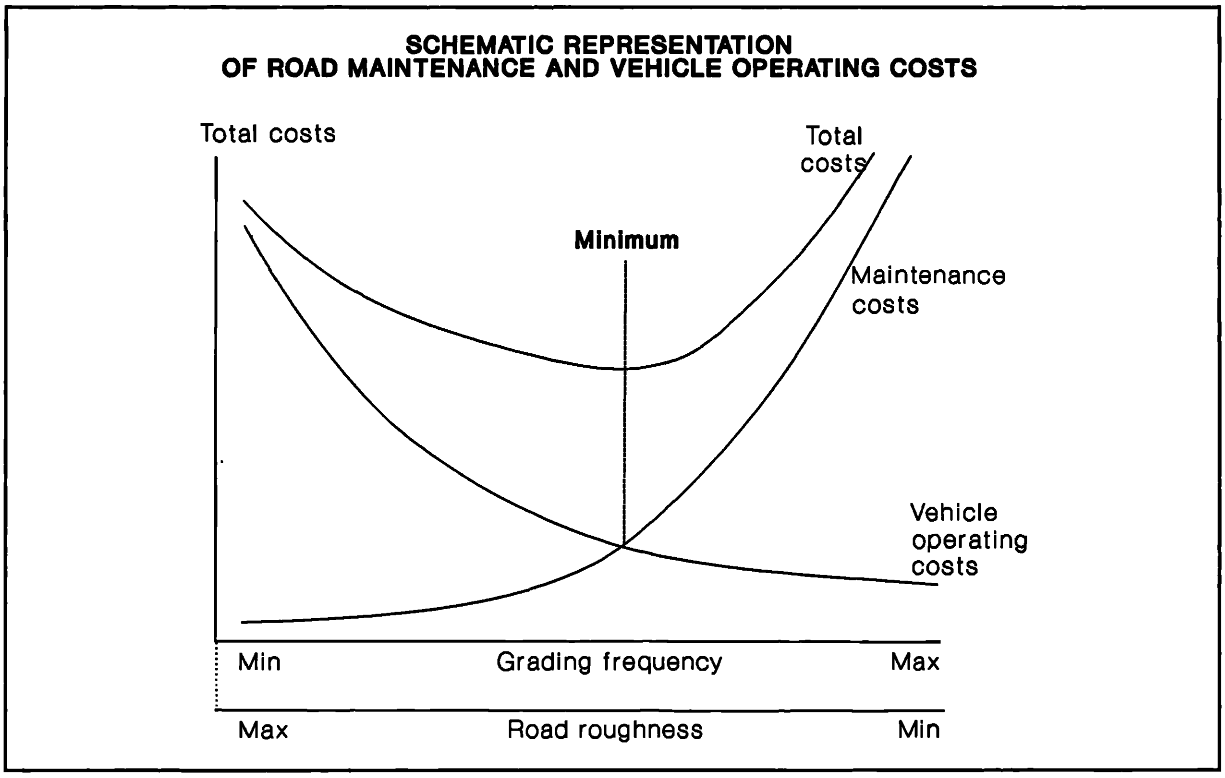


Figure 2.2 Minimisation of road maintenance and vehicle operating costs.

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.

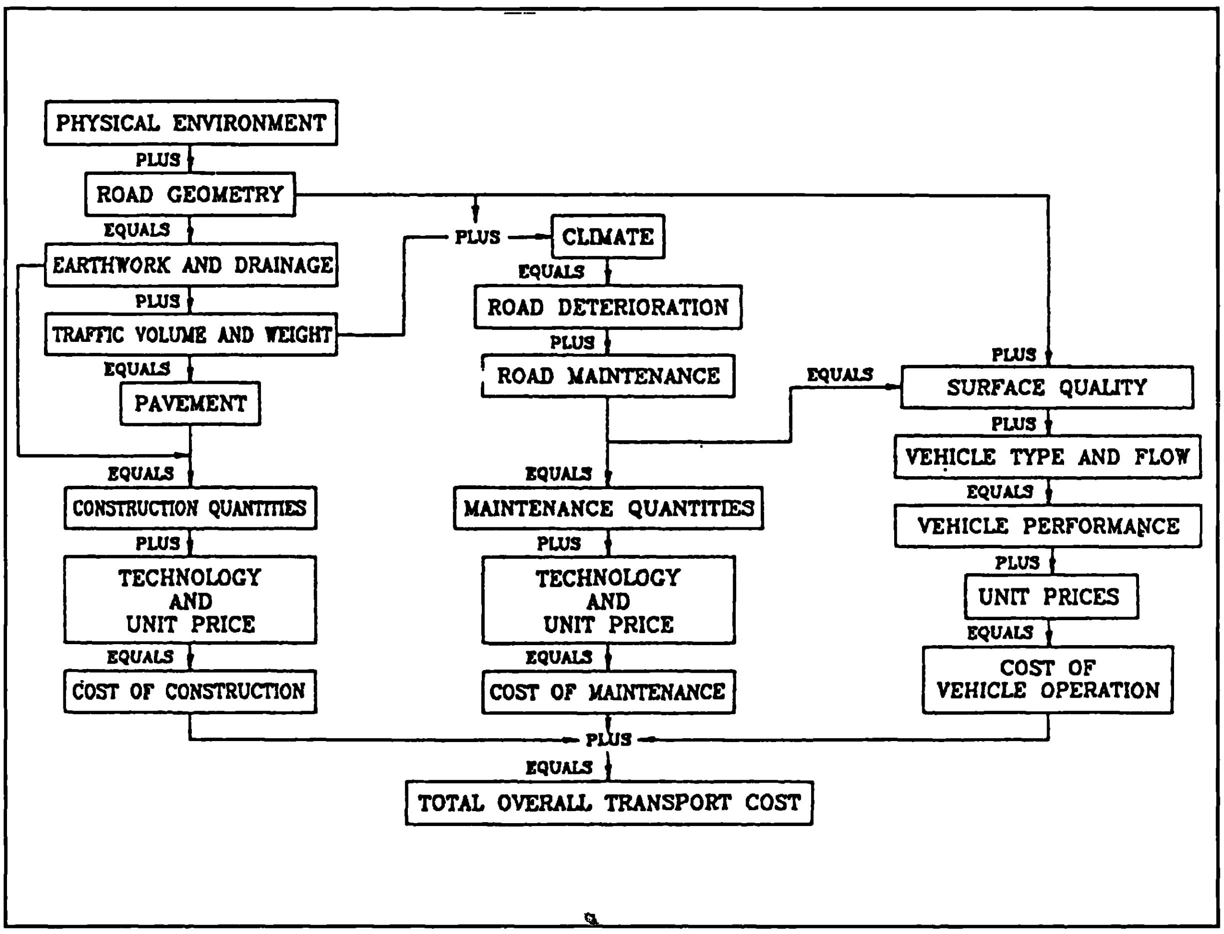


Figure 2.3 Flow Chart of the World Bank Model for Transport Cost (after Butler et al, 1979)

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.

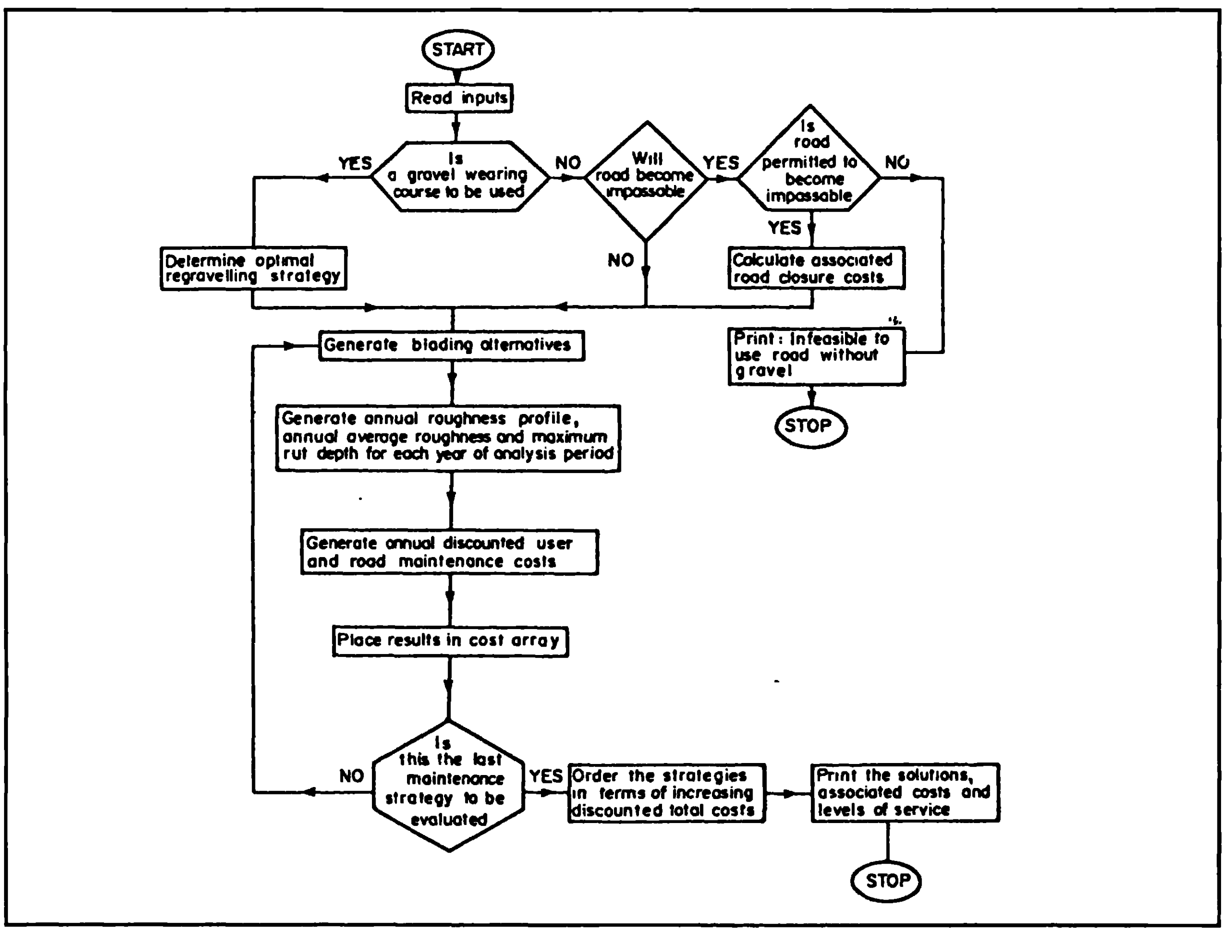


Figure 2.4 Simplified Flow Chart of the MDS (after Visser, 1981)

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

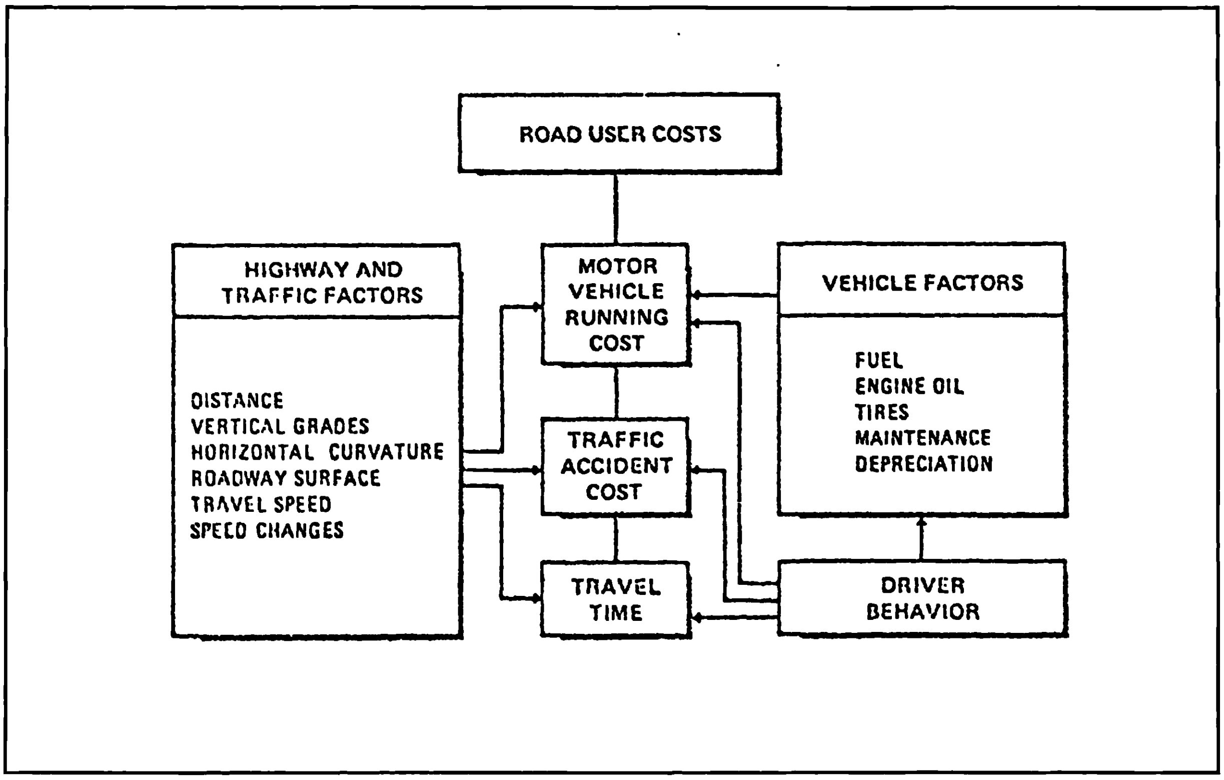


Figure 2.5 Priceable Factors of Road-user Cost Benefits (after Winfrey, 1971).

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).

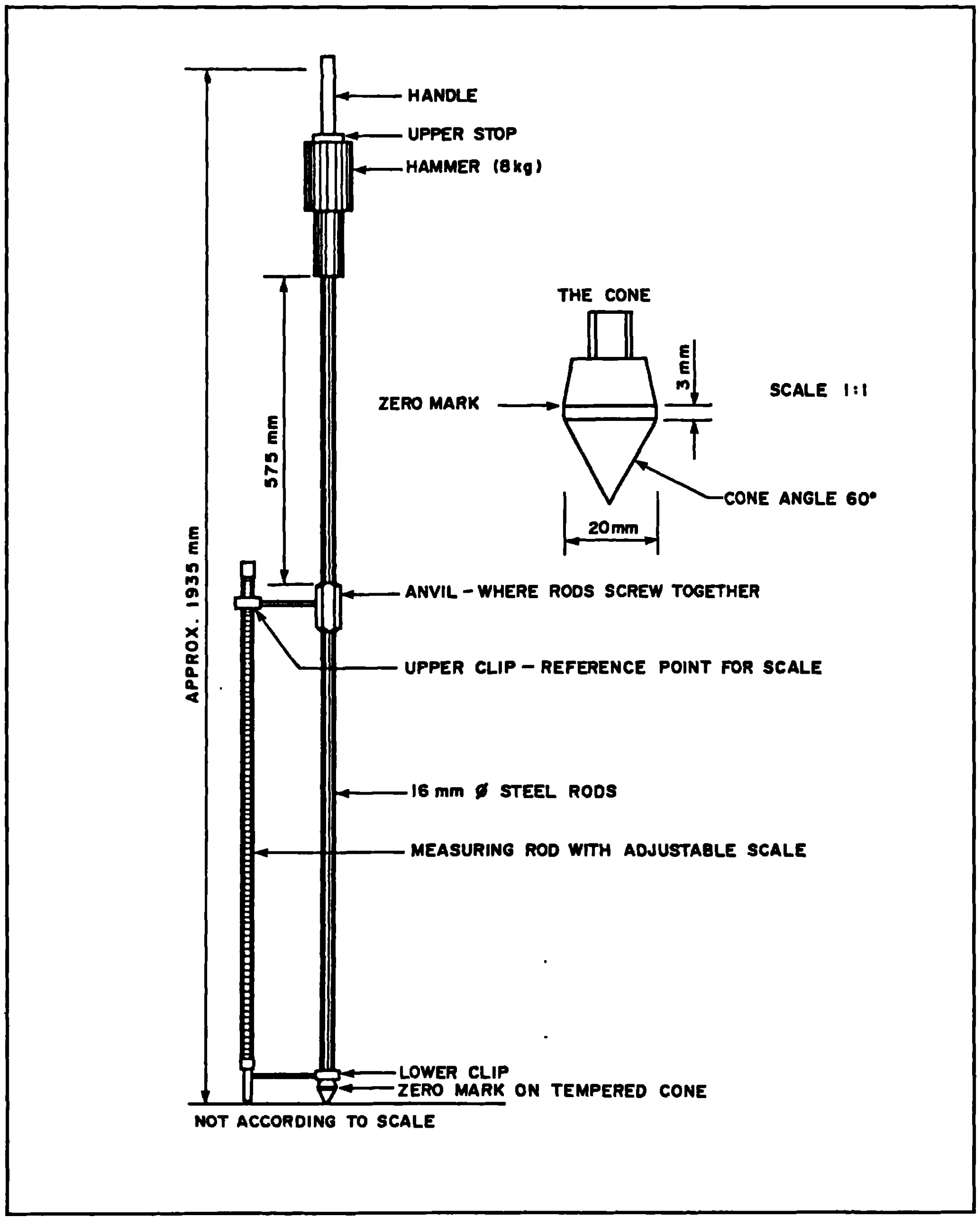


Figure 3.1 The Dynamic Cone Penetrometer (after CICTRAN, 1992).

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%.

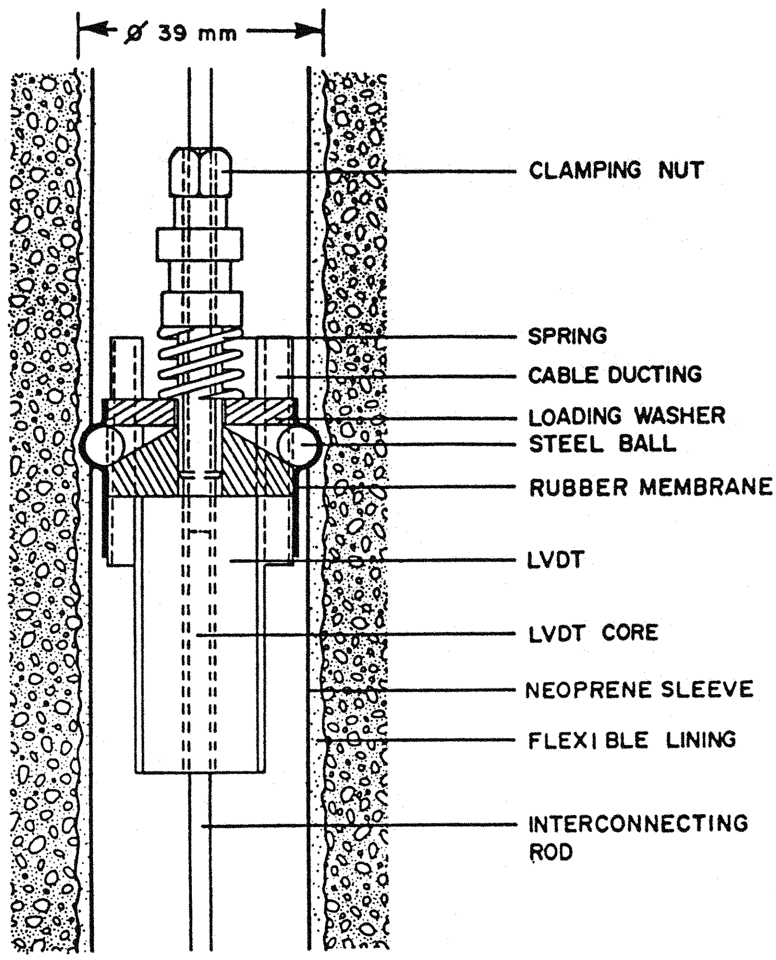


Figure 3.2 Components of a Multi-depth deflectometer (MDD) module (after De Beer et al, 1989)

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.

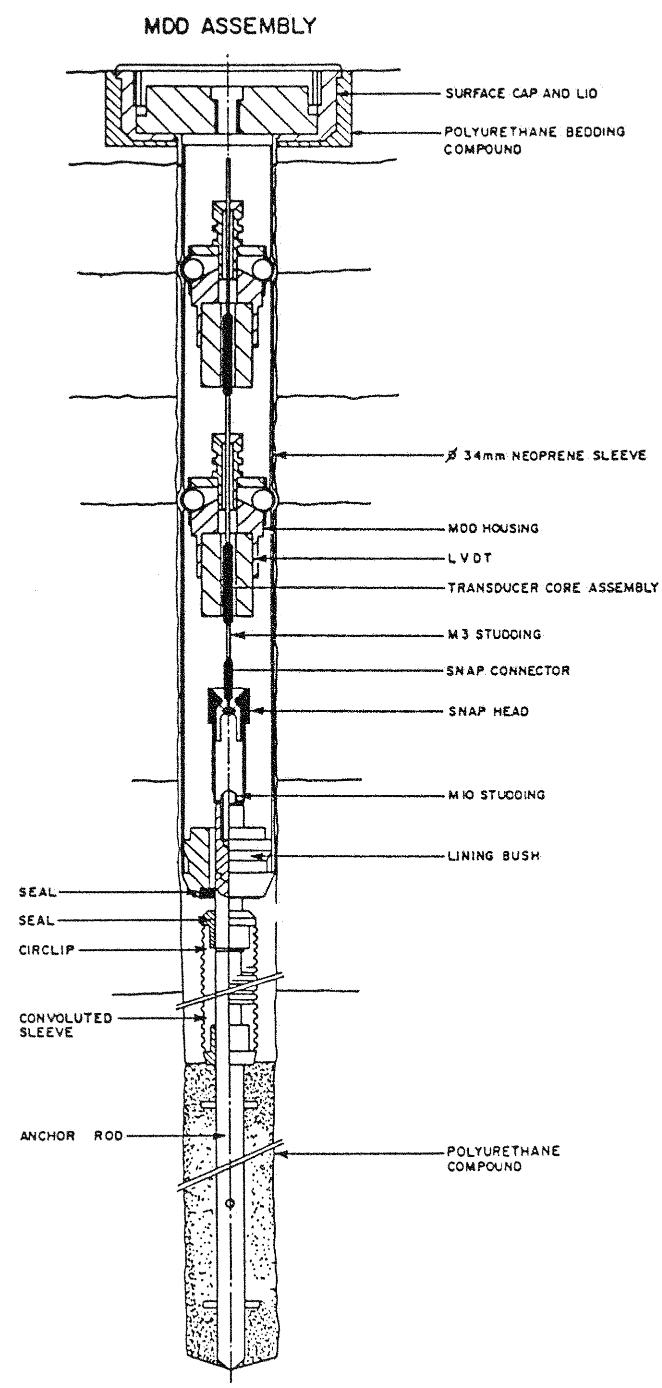


Figure 3.3 Multi-depth deflectometer in the pavement structure (after De Beer et al, 1989)

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.

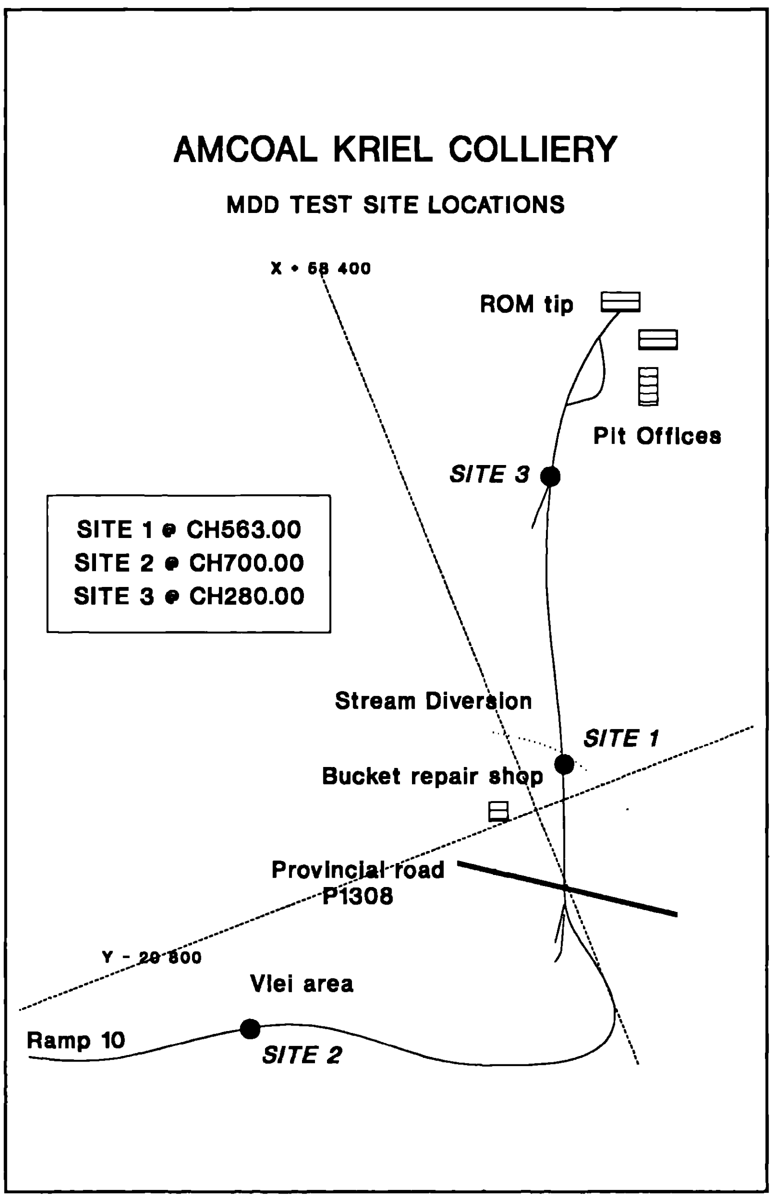


Figure 3.4 Test site locations for structural analysis - Kriel Colliery.

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** **Empty**	285 113			138 60		
Load distribution (%) **Full** **Empty**		33 48	67 52		32 47	68 53
Tyre load (kN) **Full** **Empty**		419 272	431 142		216 138	230 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.

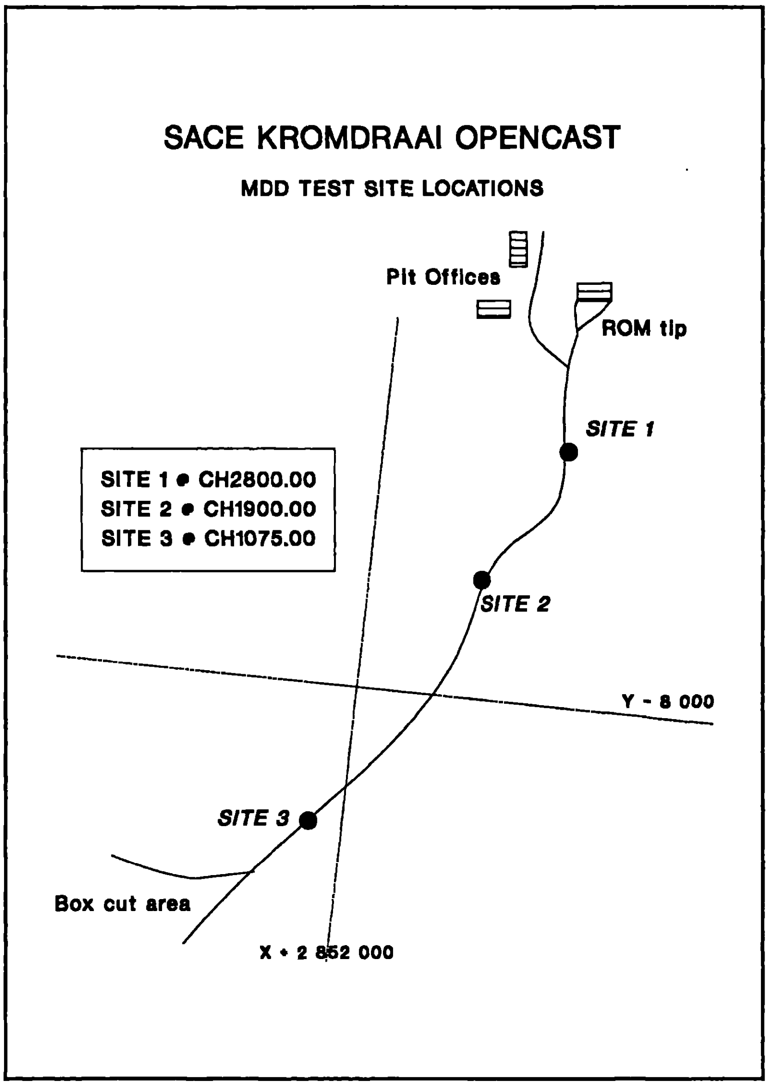


Figure 3.5 Test site locations for structural analysis - Kromdraai Colliery.

(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 Empty	257 102			138 55			267 107			85 37		
Load distribution (%) Full Empty		32 50	68 50		31 47	69 53		33 49	67 51		32 50	68 50
Tyre load (kN) Full Empty		402 250	429 127		210 127	216 78		401 257	439 134		131 92	144 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.

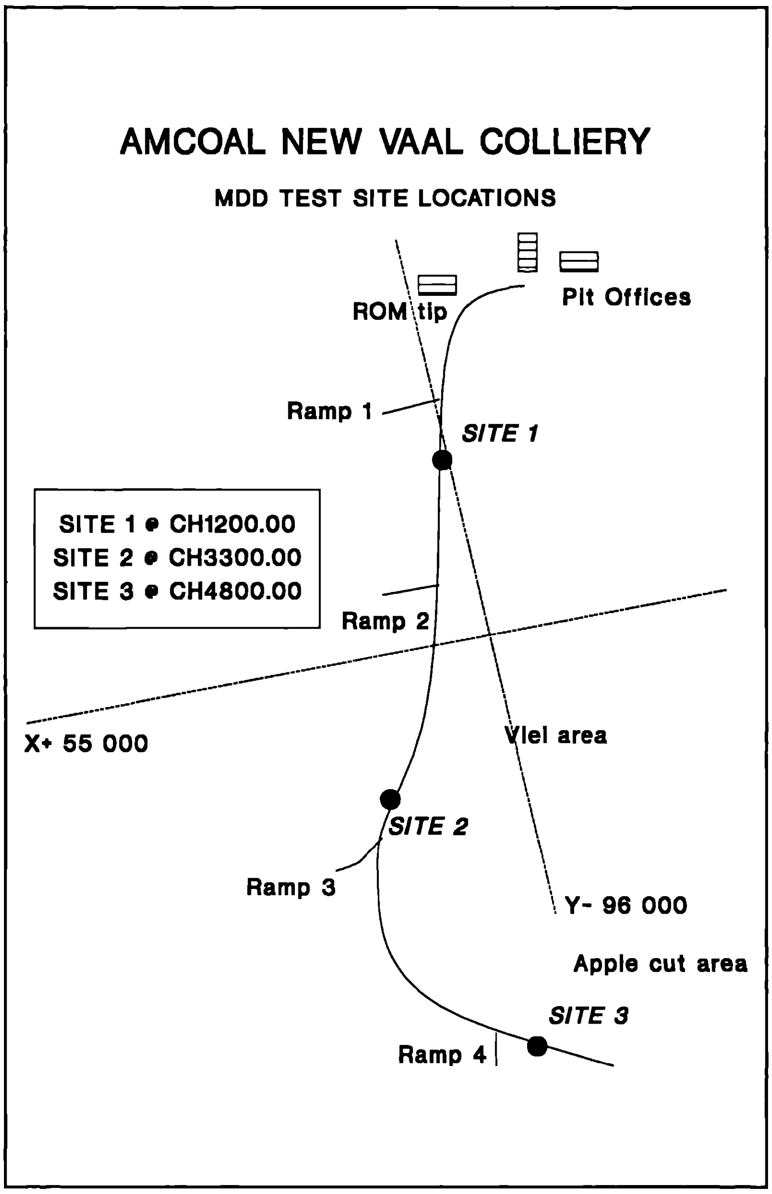


Figure 3.6 Test site locations for structural analysis - New Vaal Colliery.

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

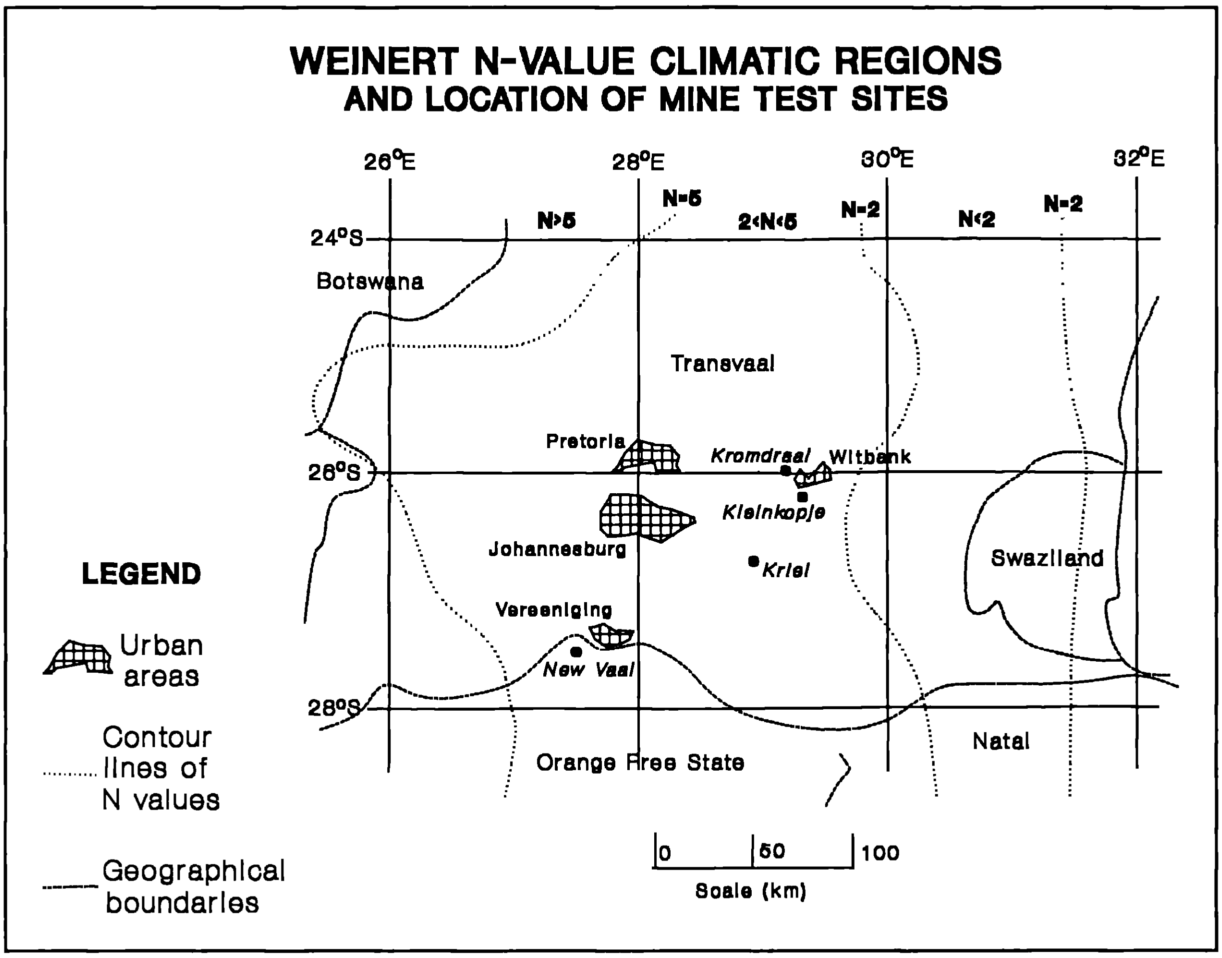


Figure 3.7 Location of Mine Test Sites in Relation to Weinert's N-values.

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

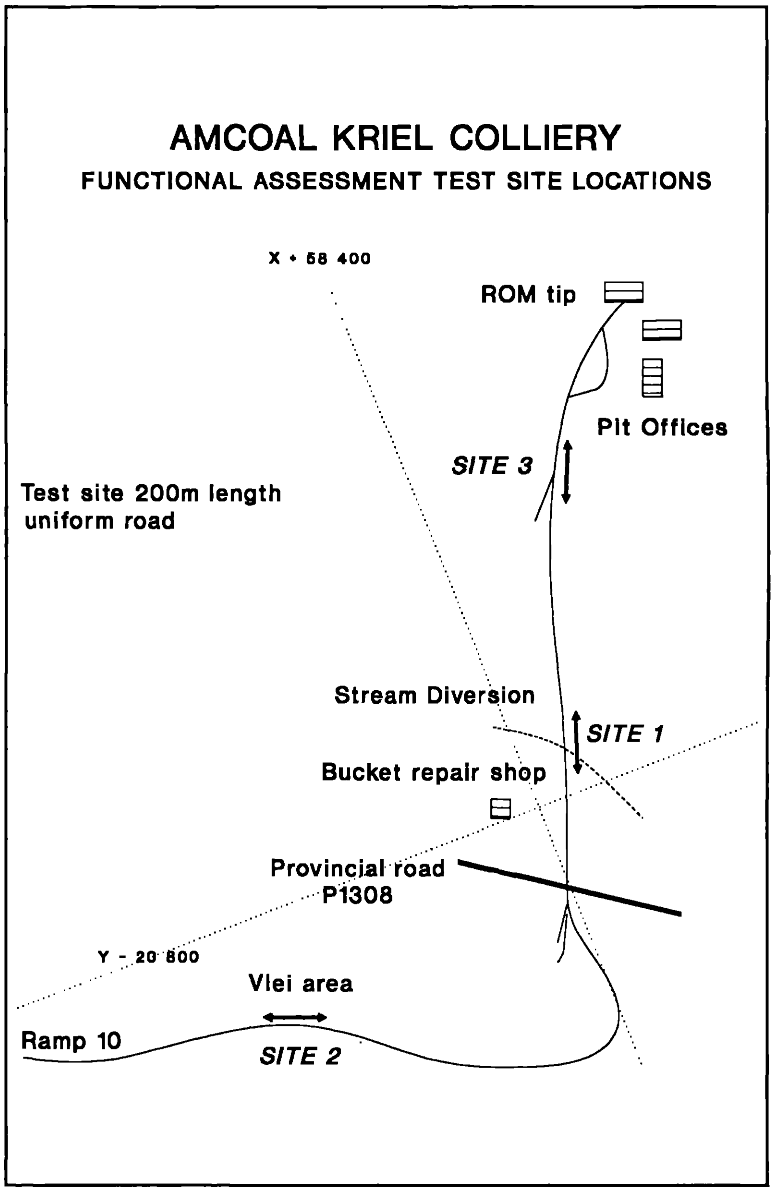


Figure 3.8 Test site locations for functional analysis - Kriel Colliery

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.

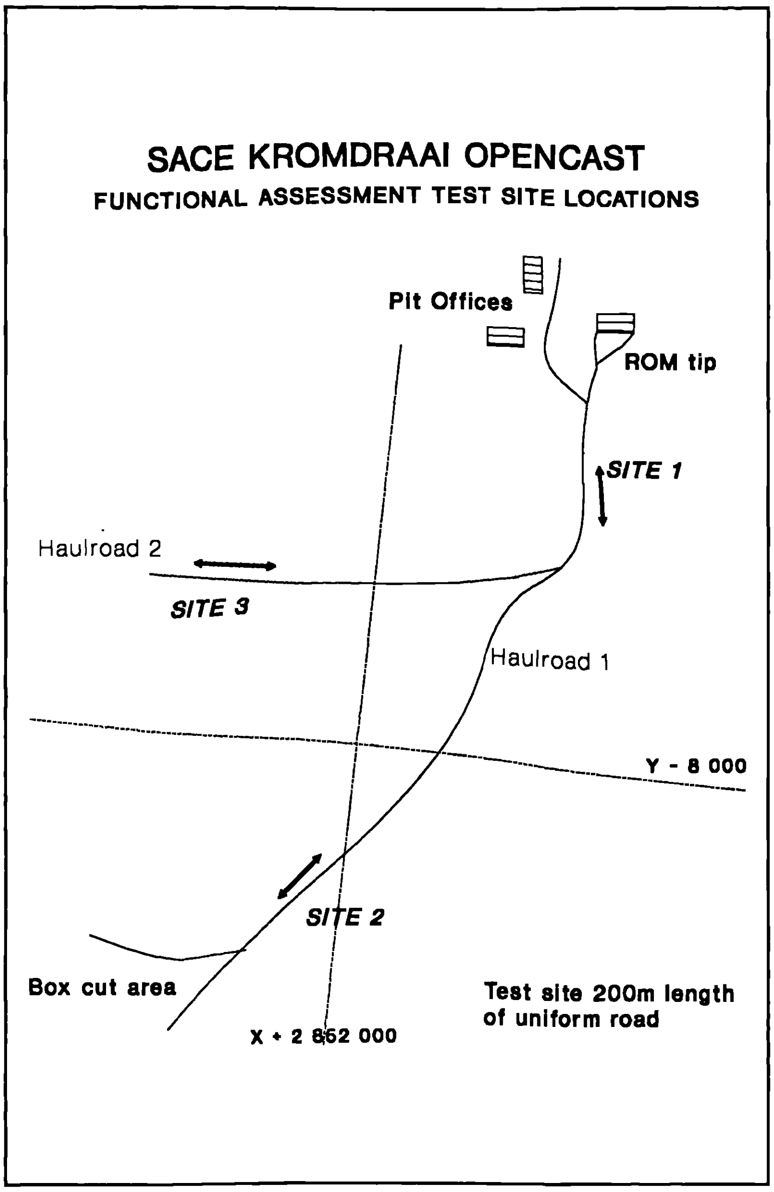


Figure 3.9 Test site locations for functional analysis - Kromdraai Colliery

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/m³)	2242	2006	1721
OMC (%)	5.2	8.7	15.0
MMC (%)	5.3	8.6	14.7
Dry density (kg/m³)	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/m³)	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/m³)	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

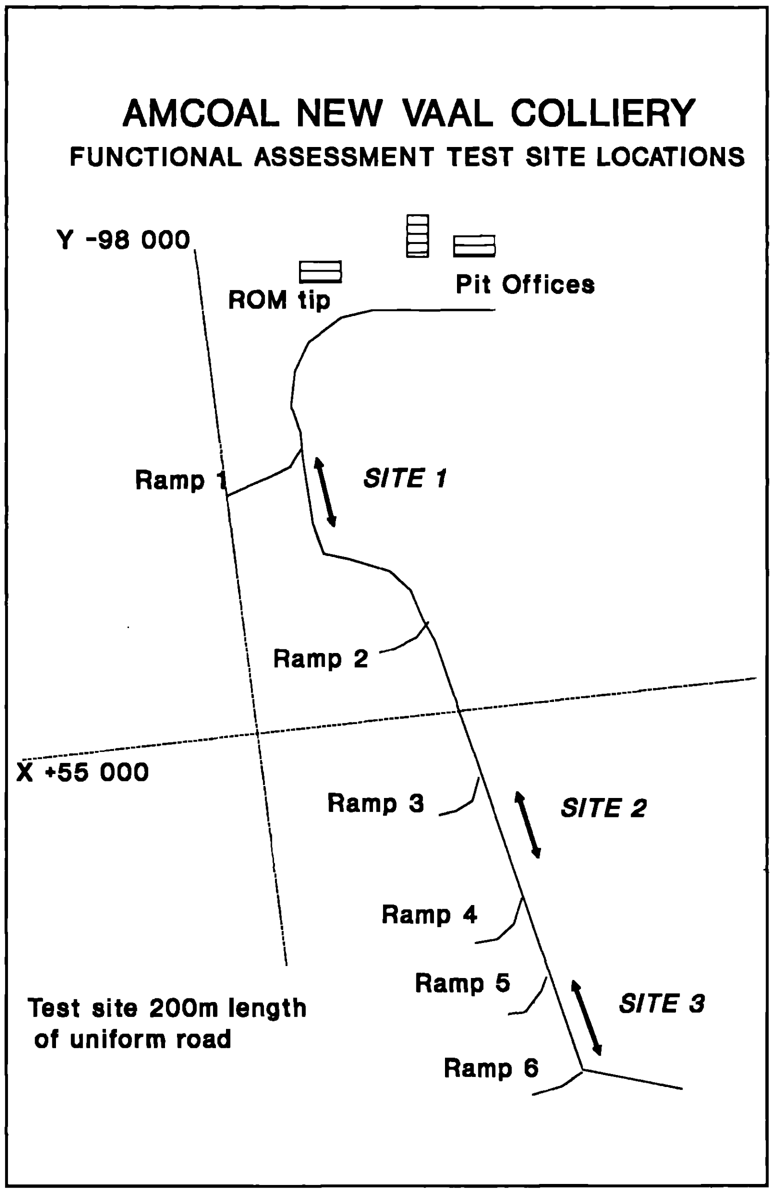


Figure 3.10 Test site locations for functional analysis - New Vaal Colliery.

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)

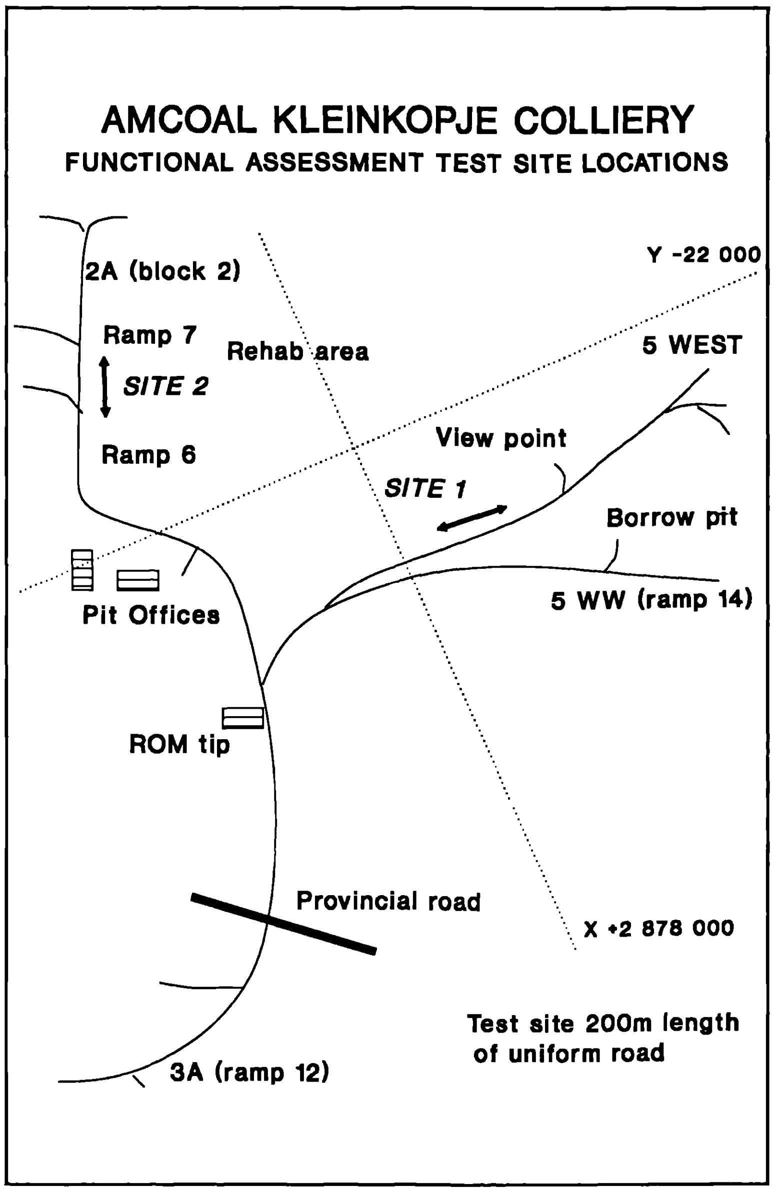


Figure 3.11 Test site locations for functional analysis - Kleinkopje Colliery

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 $N \leq 5$. 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.

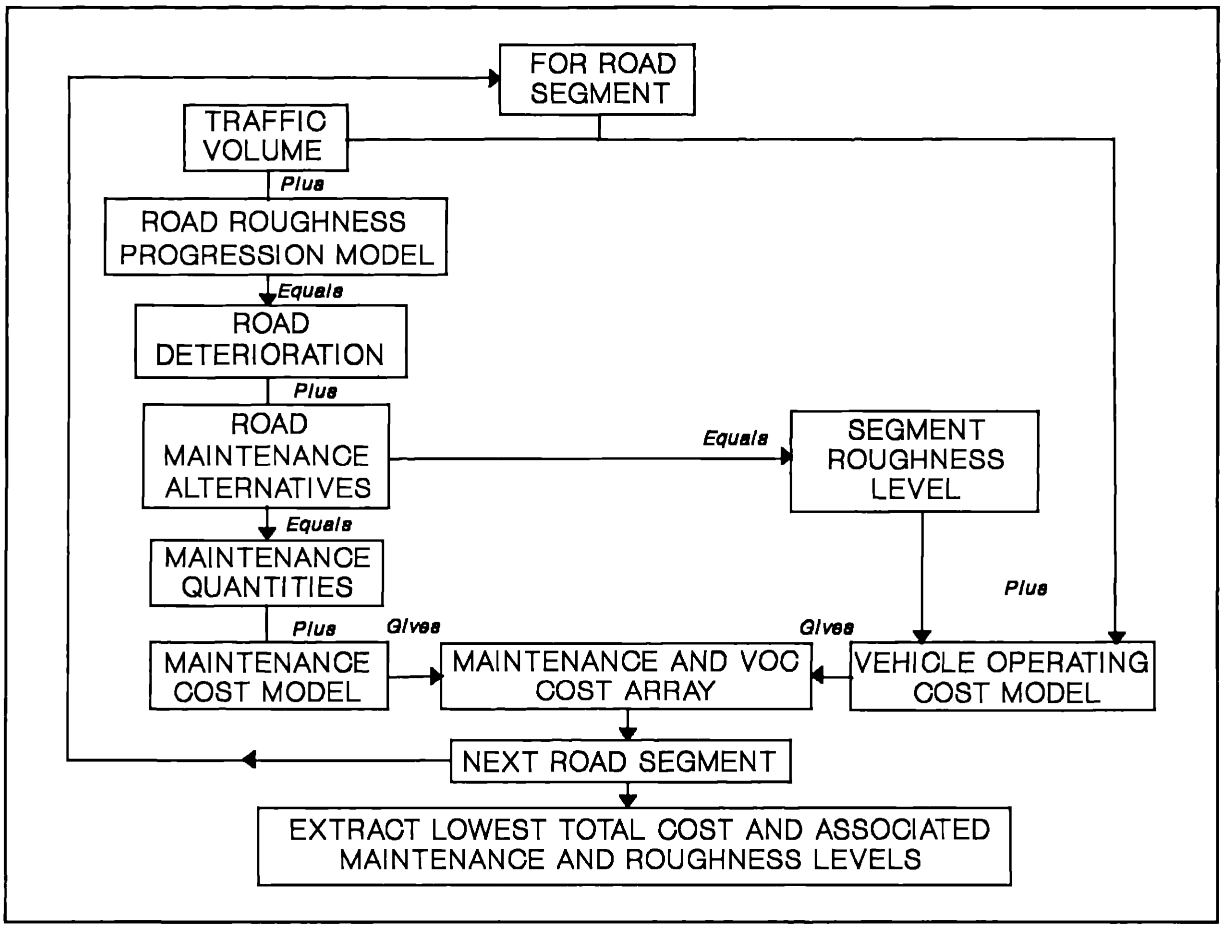


Figure 3.12 Flow Chart of Proposed MMS for Mine Haul Roads (for a single maintenance strategy iteration).

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.

CHAPTER 4
EMPIRICAL ANALYSIS AND QUANTIFICATION OF EXISTING PAVEMENT STRUCTURAL DESIGNS

4.1 Introduction

As a precursor to the mechanistic analysis of existing haul road structural designs it is necessary to determine the extent to which current empirical structural design and quantification techniques may be applied to haul road design. This chapter addresses the use of the Dynamic Cone Penetrometer in the context of haul road structural design investigations to analyse the location of various pavement layers, the California Bearing Ratio (CBR) values of these various layers and the overall balance of the structural design.

Whilst the DCP data affords an insight into the actual road structure, as opposed to the design structure and the strength of each layer actually achieved in the field, the extent to which each type of design fulfils the structural performance requirements can only be determined from analysis of the response of each layer to the applied loads. As a precursor to the analysis, the California Bearing Ratio design technique is introduced, in which CBR data generated from the DCP investigation is compared to actual cover requirements predicted from the CBR design method.

4.2 Dynamic Cone Penetrometer Analysis of Pavement Structures

Although the DCP instrument is ideally suited to the evaluation of existing pavements, the original research was used to establish a simplified design method for new pavements. This design approach is in principle similar to the CBR approach in that over-stressing of the lower layers are prevented through a balanced increase in layer strength. The DCP apparatus is used in the context of haul road structural design investigations to analyse;

- (i) the location of various pavement layers
- (ii) the California Bearing Ratio (CBR) values of these various layers
- (iii) the overall balance of the structural design

Following Kleyn et al (1982) the "DCP Structure Number" (DSN) was postulated as being a function of the thickness (h) of a layer of material and its DCP Number (DN) (mm/blow) such that:

$$Layer\ DSN = \frac{h}{DN} \qquad [4.1]$$

Thus the DSN is equal to the number of hammer blows to penetrate a certain thickness. The DCP structure number for the total pavement is thus the sum of the separate layer DSN's:

$$Pavement\ DSN = \sum_{1}^{n} \frac{h_1}{DN_1} + \ldots + \frac{h_n}{DN_n} \qquad [4.2]$$

The pavement DSN is subscripted according to the total depth of analysis, ie. DSN_{800} or DSN_{1800} depending on the method used. The information thus obtained is usually presented graphically, showing the relationship between the number of blows (horizontal axis) to the penetration depth (vertical axis). From this information, a first attempt at layer interface recognition can be made by considering changes in the slope of the graph. Typical DCP curves for a mine test site are given in Figure 4.1 from which 4 structural layers can be discerned, a medium-strong wearing course to a depth of 100mm, a strong base to a depth of 750mm followed by a weaker lower base to 1460mm and sub-base to beyond 1800mm.

The layer-strength diagram for the corresponding site, shown in Figure 4.2, is derived from the DCP curve. It relates the depth of each layer (vertical axis) to the percentage CBR on the horizontal axis. The following formulae are used;
If average penetration rate (DN) > 2mm/blow then;

$$CBR = 410 \times DN^{(-1,27)} \qquad [4.3]$$

and if DN ≤ 2mm/blow then:

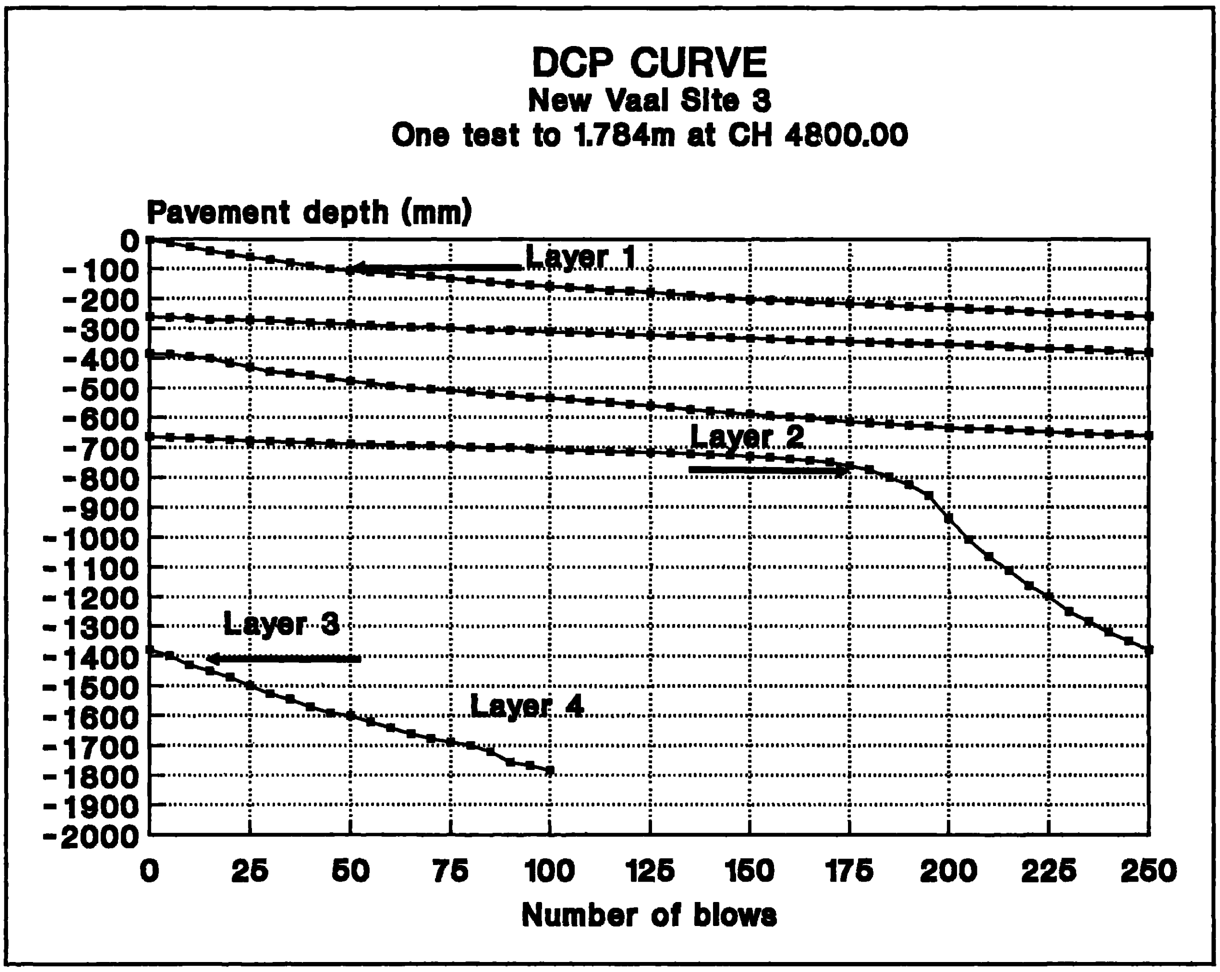


Figure 4.1 DCP Curves, New Vaal Colliery Site 3.

Figure 4.2 shows additionally the redefined CBR layer strength values from values averaged over the layer thickness. Kleyn and Van Heerden (1983) note that the correlation between CBR(%) and DN(mm/blow) is tentative above approximately 200 CBR or DN$\leq$2.

An analysis of pavement CBR values alone does not provide an objective base for interpretation and classification of road structures. The concept of strength balance is useful in providing comparative data and an insight into basic pavement behaviour. Fundamentally, the strength-balance of a pavement structure is defined as the change in strength of the pavement with depth (De Beer et al, 1988b). In general, the strength of the pavement decreases with depth and, in principle, if this decrease is smooth and without discontinuities, the pavement is regarded as being well balanced. The concept of pavement strength-balance is derived from consideration of the cumulative DSN at any point in the pavement, expressed

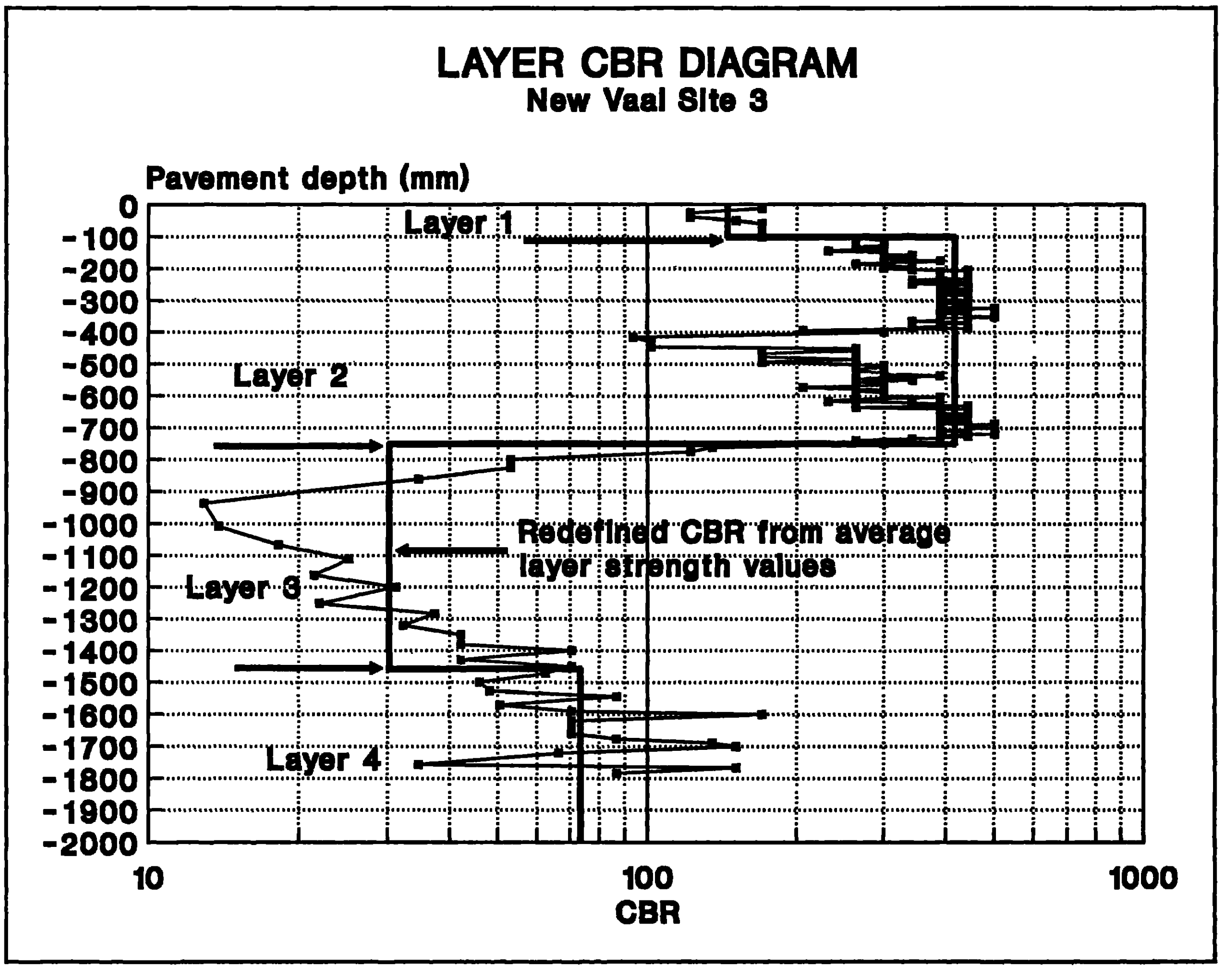


Figure 4.2 Layer Strength Diagram, New Vaal Site 3.

as a percentage of the total DSN over the full pavement depth. Standard pavement balance curves (SPBC) are used by which qualitative or quantitative assessments can be made of the deviation of the structure from a balanced design. SPBC are generated from the following formula;

$$DSN(\%) = \frac{D.[400.B + (100 - B)^2]}{4.B.D + (100 - B)^2} \qquad [4.5]$$

Where DSN = pavement structure number (%)

B = parameter describing the SPBC

D = pavement depth (%)

Figure 4.3 illustrates a number of SPBC from -60 to +60 which represent the extent that strength increases or decreases with depth respectively. The higher the SPBC number, the greater is the contribution to overall pavement strength from the upper (shallow) road layers. Deviation from a SPBC represents the state of imbalance in the structure and can be quantitatively assessed from consideration of the areal deviation (A) which represents a "goodness of fit" parameter for the pavement. For the purposes of this exercise however, a qualitative description of the strength-balance of the structure will suffice, based on the quantitative derivation of pavement strength balance categories (Kleyn et al, 1983). These are illustrated in Figure 4.4 and the corresponding descriptions given in Table 4.1.

The following ranges are recognised for SPBC and "goodness of fit" parameter A;

(i) SPBC in excess of 40 for shallow pavements, 0 to 40 for deep pavements and less than 0 for inverted structures.

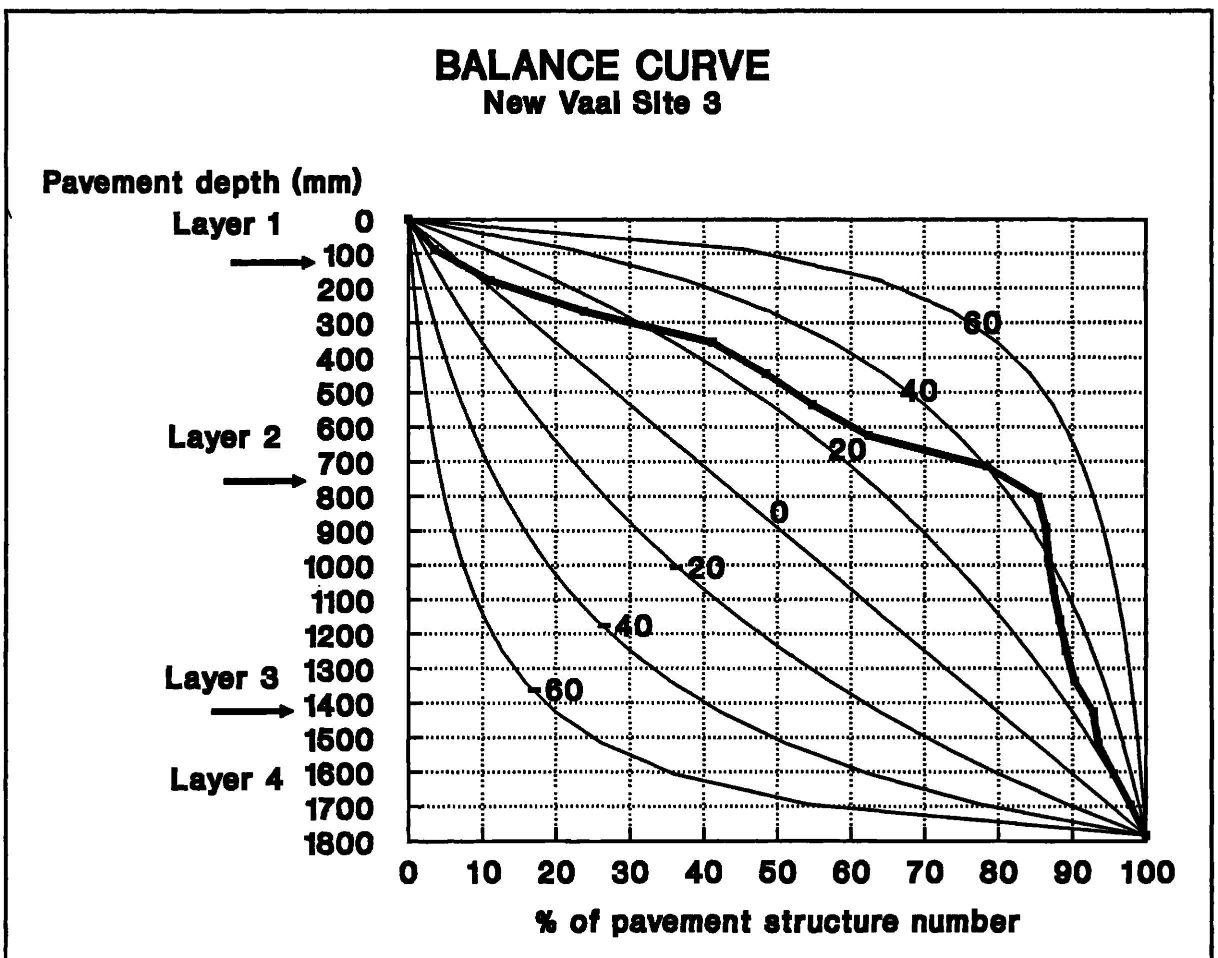


Figure 4.3 Pavement SPBC and Actual Balance Curve for New Vaal Colliery Site 3.

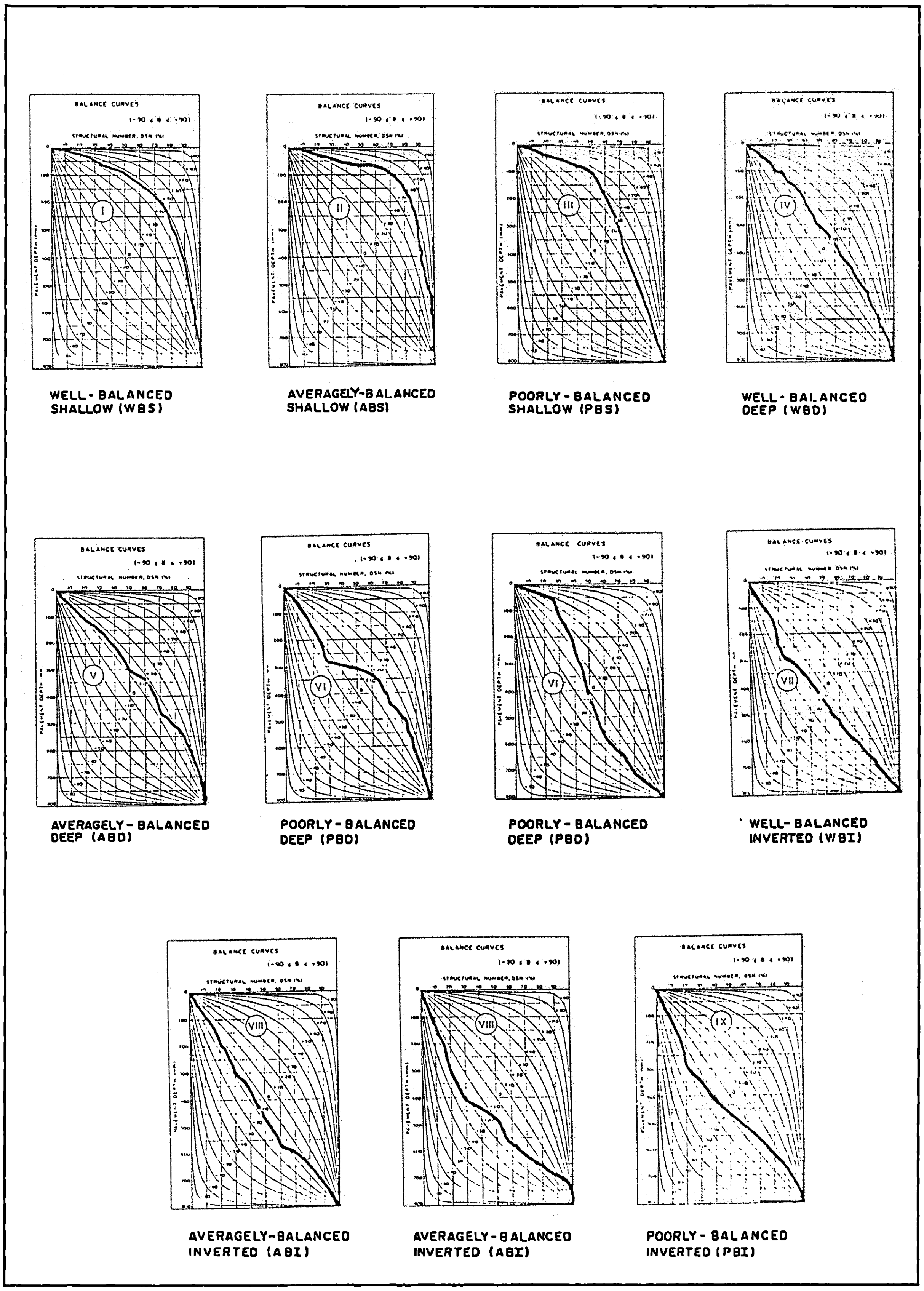


Figure 4.4 Examples of Different Structural Balance Categories (after De Beer et al, 1988b)

Table 4.1 Definition of the Nine Different Pavement Strength-balance categories (after De Beer et al, 1988b).

LIMITS FOR SPBC AND FITTING A	CATEGORY	DESCRIPTION OF CATEGORY
$B \geq 40$, $0 \leq A \leq 1200$	I	Well balanced shallow structure (WBS)
$B \geq 40$, $1200 \geq A \geq 3000$	II	Averagely balanced shallow structure (ABS)
$B \geq 40$, $A > 4000$	III	Poorly balanced shallow structure (PBS)
$0 \leq B < 40$, $0 \leq A \leq 1200$	IV	Well balanced deep structure (WBD)
$0 \leq B < 40$, $1200 \leq A \leq 3000$	VI	Averagely balanced deep structure (ABD)
$0 \leq B < 40$, $A > 3000$	VI	Poorly balanced deep structure (PBD)
$B < 0$, $0 \leq A \leq 1200$	VII	Well balanced inverted structure (WBI)
$B < 0$, $1200 < A \leq 3000$	VIII	Averagely balanced inverted structure (ABI)
$B < 0$, $A > 3000$	IX	Poorly balanced inverted structure (PBI)

(ii) A from 0 to 1200 for a well balanced pavement, 1200 to 3000 for average and in excess of 3000 for poorly balanced.

A typical strength balance curve is illustrated in Figure 4.3 for New Vaal Colliery site 3 from which it is seen the road corresponds to a poorly balanced deep structure. The inferences and implications of the above assessments are discussed for each mine site in the following section. DCP curves, layer CBR and strength balance curves for each site are given in Appendix B.

4.2.1 Discussion of DCP Analysis - Kriel Colliery

The pavement profiles and corresponding CBR values of each layer as determined from the DCP analysis and road construction plans are presented for each site in Figure 4.5 and discussed in the proceeding sub-sections.

Site 1

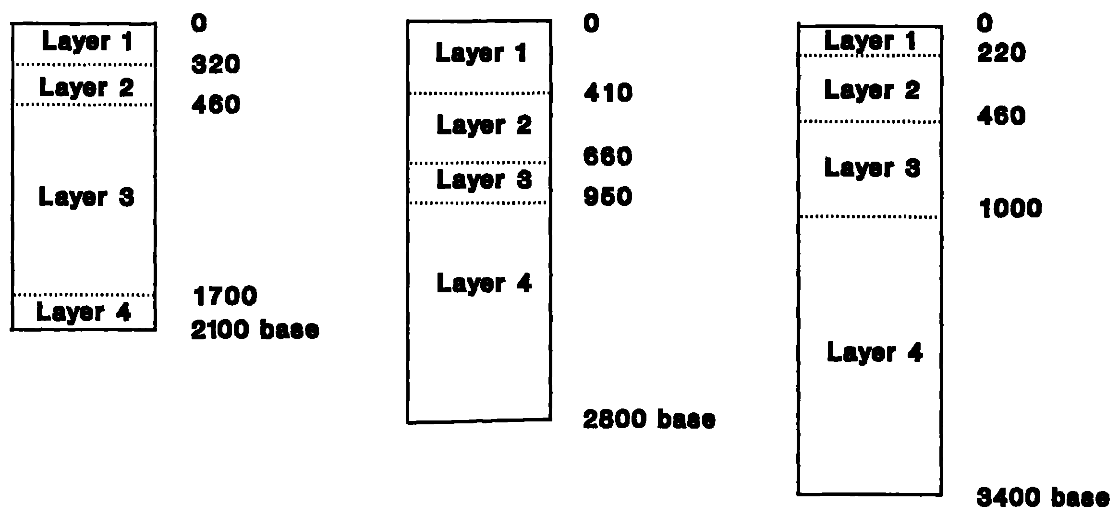
Four structural layers were discerned at site 1; a medium-strong wearing course to a depth of 320mm, a medium-weak base 140mm in thickness, a very weak sub-base to a depth of 1700mm and medium-weak selected material layer beyond that. The average CBR values calculated for the layers correlated closely to recorded values, except in the case of the transition between layers 1 and 2 and some large CBR variations in layer 3, albeit over less than 100mm. This is indicative of isolated pockets of poor quality material in the construction.

The balance of the pavement may be described as an averagely balanced shallow structure, although the curve lies below the SPBC=40 curve, since the majority of the strength of the pavement lies in the upper 2 layers.

Site 2

Four layers are discerned at site 2; a medium-weak wearing course extending down to 410mm, followed by a strong base to a depth of 660mm, a very strong sub-base to 950mm

KRIEL PAVEMENT PROFILES



Site 1

LAYER	CBR
1	228
2	56
3	27
4	58

Site 2

LAYER	CBR
1	85
2	178
3	227
4	141

Site 3

LAYER	CBR
1	118
2	428
3	240
4	32

Figure 4.5 Kriel Colliery Pavement Profiles as Determined by DCP Analysis.

and a strong lower sub-base to beyond 1264mm. Layer 1 correlates well with the average CBR value found, but layers 2 and 3 reveal the existence of isolated strong and weak spots within the structure.

The balance of the pavement is thus described as an averagely balanced inverted structure which is borne out by the CBR values of the pavement layers, the strength increasing with depth. From layer 3 onwards, the structure reverts to a well balanced deep structure due to the decreasing layer strength values beyond this point.

<u>Site 3</u>

Four structural layers are discerned at this site consisting of a medium-strong wearing course extending to a depth of 220mm lain upon a stabilised (5% hydrated lime) base 240mm thick which exhibits particularly high CBR values. The sub-base is also of medium strength whilst the lower sub-base consists of weak material beyond a depth of 1939mm. Layers 2 and 3 correlate well with the average CBR calculated whilst layers 1 and 4 show some scatter. In the case of the former a hard compacted layer some 25mm deep is seen to form in the wearing course under the action of heavy traffic.

The balance of the pavement is thus described as a poorly balanced shallow structure, primarily due to the action of the stabilised base which moves the curve from an inverted structure above a depth of 220mm to a well balanced shallow structure below a depth coincidental with the end of the stabilised layer.

4.2.2 Discussion of DCP Analysis - Kromdraai Colliery

The pavement profiles and corresponding CBR values of each layer as determined from the DCP analysis are presented for each site in Figure 4.6 and discussed in the proceeding sub-sections.

<u>Site 1</u>

Four structural layers are discerned at this site, a very strong wearing course 200mm thick lain upon a strong base 250mm thick, below this the sub-bases are weak down to a measured depth of 1906mm and beyond. CBR values redefined from average layer strength values correspond well with actual values recorded although the latter show a gradual decrease in strength with depth as opposed to the definite layer boundaries assumed for the layer locations.

The balance of the pavement is thus described as a well balanced shallow structure, the majority of the structural strength being seen in the upper two layers of the structure.

<u>Site 2</u>

Four structural layers were discerned at this site, the wearing course extending down to 100mm consists of very strong material lain upon a strong base extending down to 470mm. Below this the sub-bases are weak, with the lower sub-base particularly weak down to a depth of 1911mm and beyond. Redefined CBR values correspond closely to those measured

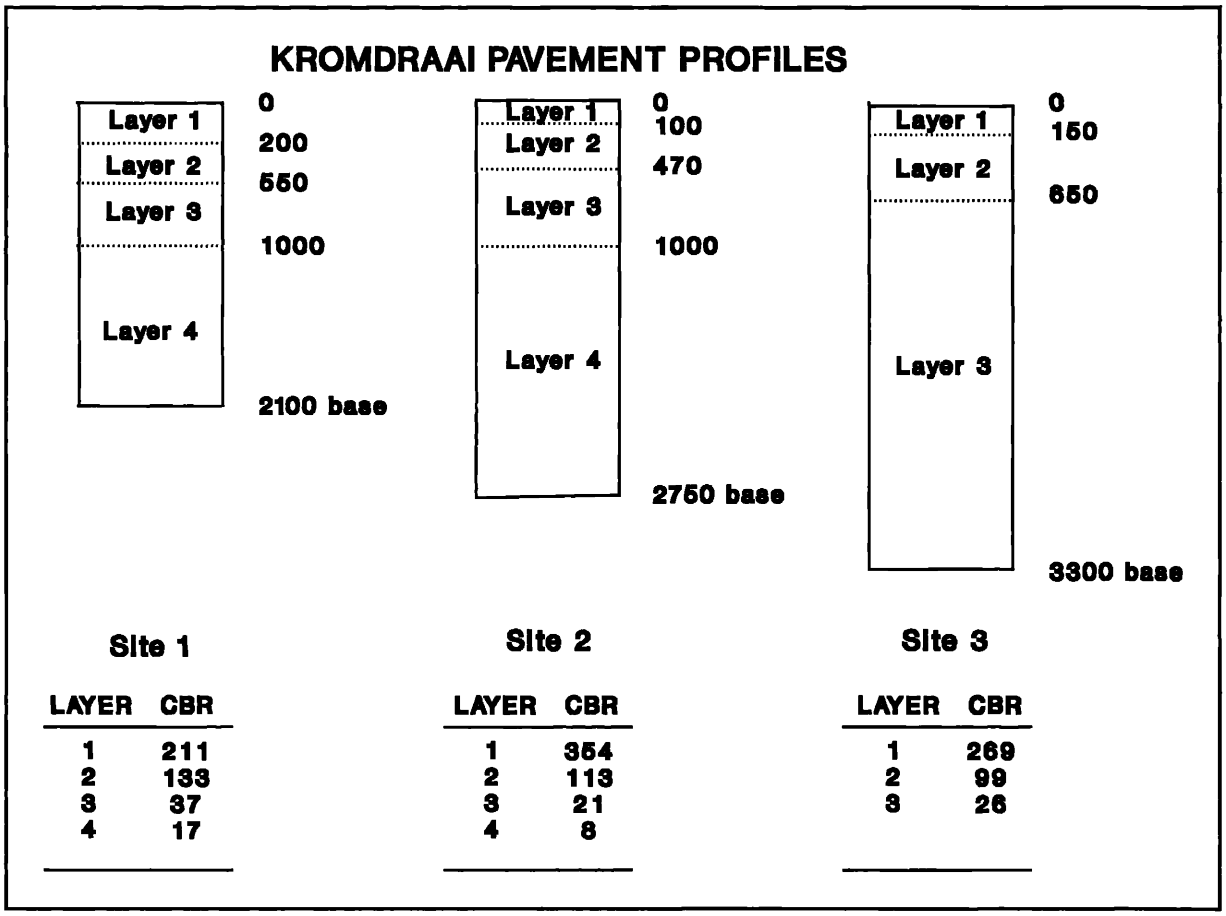


Figure 4.6 Kromdraai Colliery Pavement Profiles as Determined by DCP Analysis.

for each layer except for layer 3 where a gradual decrease in strength with depth is apparent. No significant strong or weak spots were seen in the structure.

The balance of the pavement is thus described as a well balanced shallow structure, in terms of balance one of the best sites investigated as shown in Figure 4.7. (Refer to Appendix B for the complete results).

Site 3

Three structural layers were discerned at this site consisting of a strong wearing course layer 150mm deep lain upon a medium strong base of 500mm thickness and a sub-base of weak material down to a measured depth of 1881mm and beyond. There is a gradual decrease in strength with depth over layers 1 and 2 whilst layer 3 exhibits isolated strong and weak spots about an average CBR value of 26.

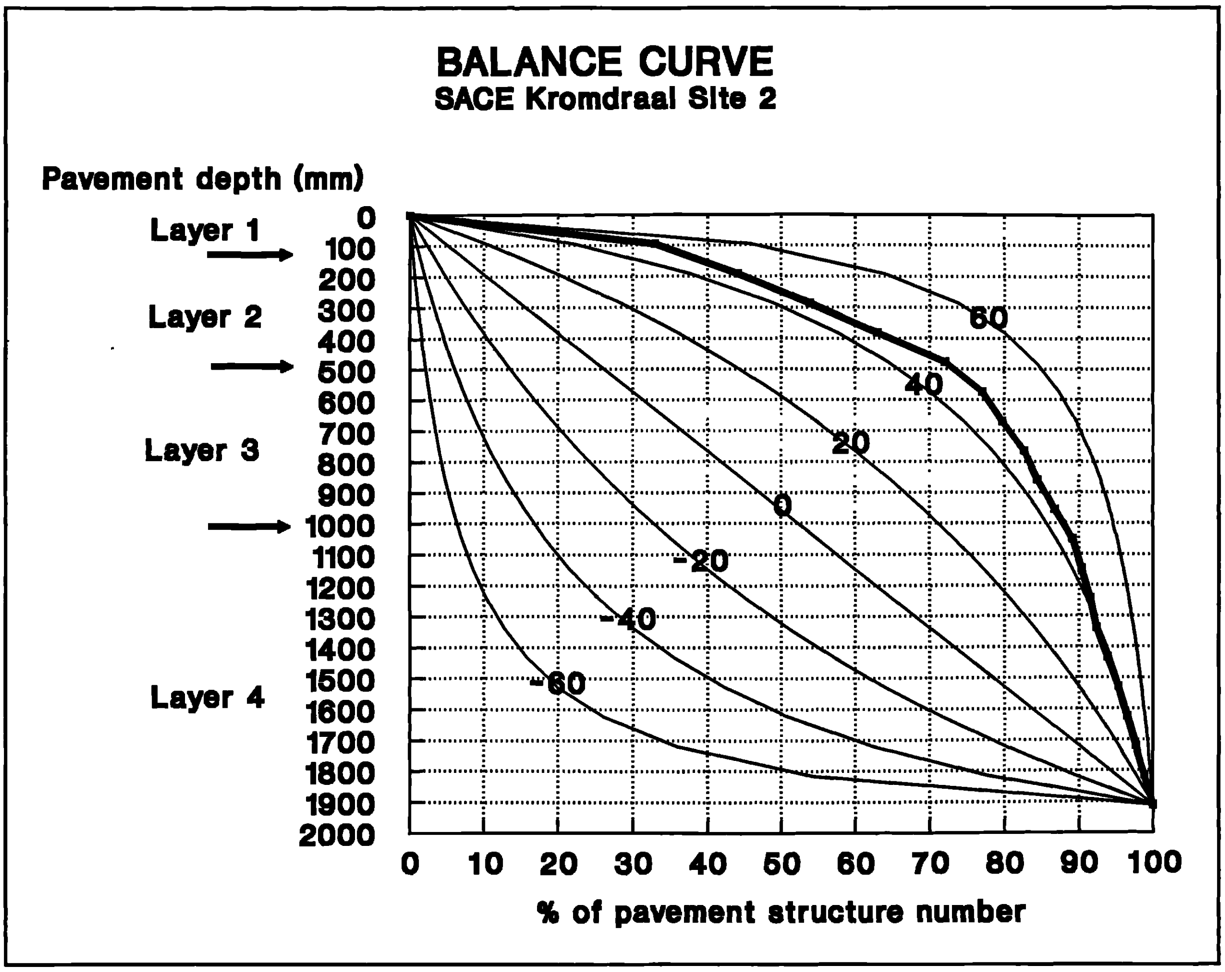


Figure 4.7 Particularly Well Balanced Shallow Structure at Kromdraai Mine Site 2.

The balance of the pavement is described as an averagely balanced shallow structure, primarily arising from the rapid degradation of strength with depth in layer 3.

4.2.3 Discussion of DCP Analysis - New Vaal Colliery

The pavement profiles and corresponding CBR values of each layer as determined from the DCP analysis are presented for each site in Figure 4.8 and discussed in the proceeding sub-sections.

Site 1

Four structural layers are discerned at site 1 consisting of a strong wearing course 100mm

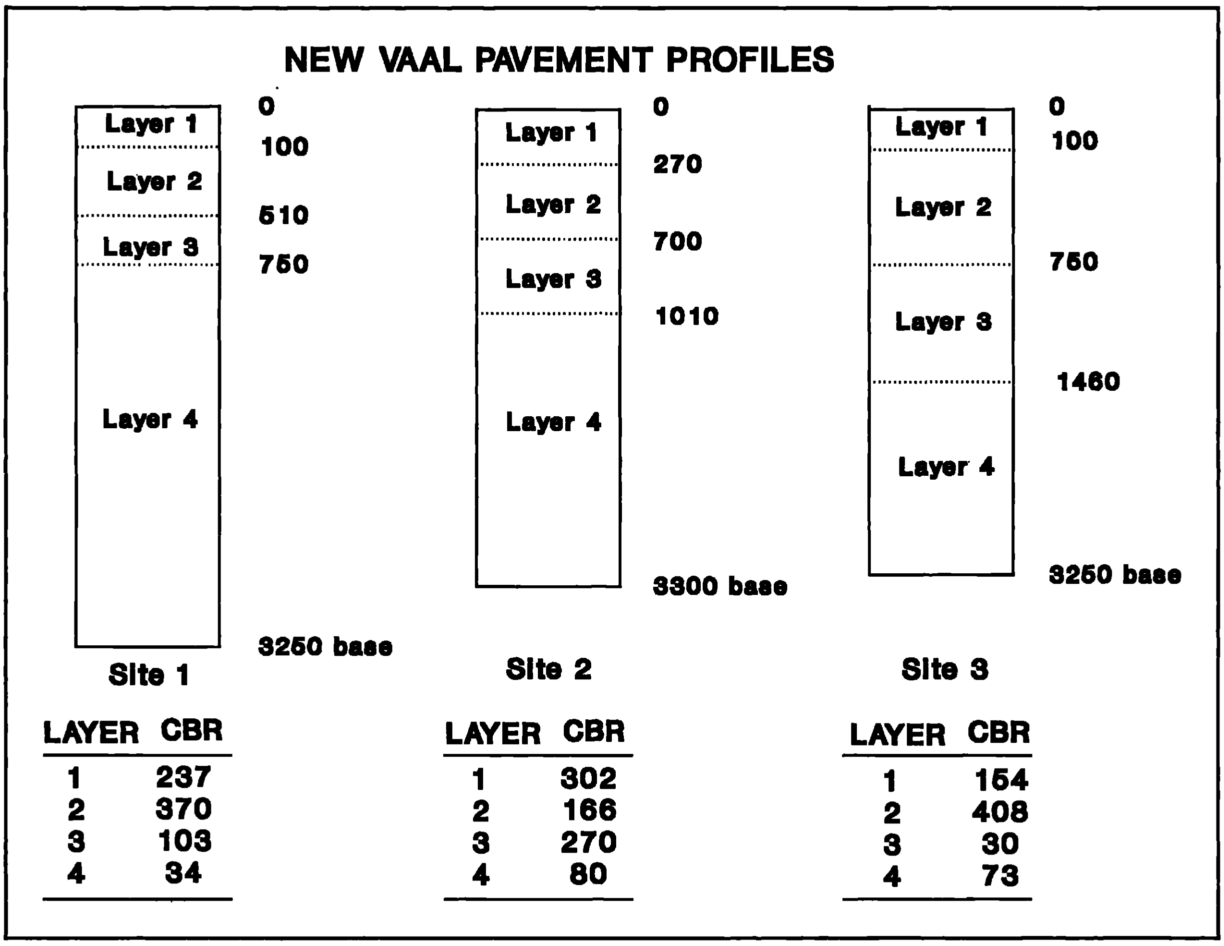


Figure 4.8 New Vaal Colliery Pavement Profiles.

in thickness followed by a very strong base 410mm in thickness. These are lain upon a moderately strong and weak sub-base layers 240mm and in excess of 509mm (respectively) in thickness. CBR values calculated from actual values show some deviation about the mean value in layers 1 and 2 but remain approximately constant with depth. Layer 3 exhibits a gradual decrease of strength with depth over the layer whilst layer 4 is again relatively constant in strength. The refusal of the penetrometer at 1259mm depth gives rise to spuriously high values in the last 150mm depth of probing which are ignored for calculation purposes.

The balance of the pavement is thus described as a poorly balanced deep structure, primarily due to the strong base layer 2 lain upon the much weaker sub-base layers 3 and 4. A degree of imbalance in the lower levels of the pavement may be ascribed to the penetrometer refusal and apparent increase in strength in this region.

Site 2

Four structural layers are discerned at this site consisting of a very strong wearing course 270mm thick placed upon a strong base 430mm thick. The sub-base layers consist of a very strong upper layer 310mm thick and a moderately weak lower layer to a depth of 1620mm and beyond. The CBR values show considerable scatter for all layers but the general trend of layer strengths is evident from the redefined CBR layer values.

The balance of the pavement is thus described as an averagely balanced deep structure primarily due to the influence of layer 3 at 700mm - 1010mm depth providing structural strength at depth.

Site 3

Four layers are discerned at this site, the wearing course being moderately strong and 100mm in thickness. The base layer 2, extending from 100mm to 750mm is particularly strong and is lain upon a very weak upper sub-base 710mm in thickness. The lower sub-base extends to 1784mm and beyond and is moderately weak. CBR values calculated for each layer correlate well with actual values in layers 1 and 2 whilst layer 3 exhibit isolated weak spots and an overall trend of increasing strength with depth. Layer 4 shows isolated weak and strong spots but no specific trend of strength with depth.

The balance of the pavement is thus described as a poorly balanced deep structure, primarily as a result of the particularly strong base layer 2.

4.3 DCP Analysis Summary

Table 4.2 presents a summary of the DCP results and should be read in conjunction with Figures 4.5, 4.7 and 4.8. The results presented confirm the classification of test sites proposed in Table 3.6 for the site location matrix, envisaged in the experimental design.

In general, those sites showing a shallow structure, in which the majority of the pavement strength lies in the upper layers may be more sensitive to increased wheel loads and consequential failure of the upper layers. A deep structure, in contrast, would be less sensitive to any increase in wheel loads, but may well show signs of excessive deformation in the weaker upper layers. The extent to which these effects are seen in haul roads can only be determined from in-situ deflection measurements.

Table 4.2 Summary of DCP Results - Pavement Balance

MINE	TEST SITE	PAVEMENT DESCRIPTIVE SUMMARY
Kriel Colliery	1	Averagely balanced shallow structure
	2	Averagely balanced inverted structure
	3	Poorly balanced shallow structure
Kromdraai Colliery	1	Well balanced shallow structure
	2	Well balanced shallow structure
	3	Averagely balanced shallow structure
New Vaal Colliery	1	Poorly balanced deep structure
	2	Averagely balanced deep structure
	3	Poorly balanced deep structure

In addition, the pavement strength-balance concept focuses on the upper 1,8m of material, which, for most mine sites generally includes a portion of sub-grade. The strength-balance concept does not address whether the pavement as a whole is suited to the sub-grade strength. Thus, although the DCP data affords an insight into the actual road structure as opposed to the design structure and the strength of each layer actually achieved in the field, the extent to which each type of design fulfils the structural performance requirements can only be determined from analysis of the response of each layer to the applied loads. As a precursor to the analysis, the California Bearing Ratio design technique is investigated in which CBR data generated from the DCP investigation is compared to actual cover requirements predicted from the CBR design method.

4.4 California Bearing Ratio (CBR) Design Procedure

A survey conducted in 1928-1929 by the California Roads Department to determine the extent and cause of road pavement failures concluded that failure was caused by either inadequate compaction of materials forming the road layers and/or insufficient cover over weak in-situ material. These conclusions indicated the importance of material compaction and shear strength considerations in road building, both in terms of a suitable design procedure and an associated materials testing method (Yoder and Witczak, 1975). The notion of the California Bearing Ratio (CBR) value for a specific material was thus developed from a laboratory penetration test of a soaked sample of pavement material as an inference of its shear strength. The CBR value for a material is thus the relationship between the force necessary to drive a piston into the sample and the force to likewise drive the piston into a standard gravel sample upto a given depth, usually 2,54mm, results being reported as a percentage of the standard (gravel) test.

The first indictions of cover requirements over in-situ materials of specific CBR (%) values was reported by the California Division of Highways during the years 1928-1929 (American Society for Civil Engineers, 1950). Later modifications included consideration of (air) traffic volumes, single wheel loads and increased wheel loads based on an estimated maximum allowable shear stress for specific materials. The problem of dual wheel assemblies was addressed by Boyd and Foster (1949) through consideration of the Equivalent Single Wheel Load (ESWL), where a load is calculated which generates the same tyre contact area and maximum deflection as would the group of wheels. The concept of equivalent deflection is used to equate an equivalent single wheel to the multiple wheel group.

Traffic volume and its effect on the structural design of pavements was considered by Ahlvin et al (1971) in which a repetition factor was determined according to load repetitions and the total number of wheels used to determine the ESWL. In this manner, the resulting thickness of cover could be modified to accommodate air traffic volumes.

Despite the empirical origins of the technique, Turnbull and Ahlvin (1957) derived a mathematical approach to the calculation of cover requirements using the CBR method. This approach is adopted for the calculation of cover requirements over in-situ material, as predicted by the CBR design method for ultra-heavy axles.

4.4.1 Mathematical Correlation

The contact pressure and distribution between any tyre and the pavement depends on tyre pressure, wheel load and tyre construction. The contact area is generally approximated as circular, although an analysis of heavy vehicle tyre loads has shown this only to be true when the ratio between applied load and maximum rated load is small (Marshek, 1978, Tielking and Roberts,1987). Mine haul trucks fully loaded exhibit ratios of between 0,7 to 0,9 of manufacturers recommended payload (Goodyear, 1990) and the contact area approximates more to a rectangle. Additionally, contact pressure is assumed to equate to tyre inflation pressure which is an over simplification; upto 10% variation may occur between tyre and contact pressure under ideal inflation conditions, greater variations with increased deviation from recommended inflation pressures. For the purposes of the CBR analysis, Goswami and Bhasin (1986) illustrated that more refined modelling of these two parameters is not warranted and the only deviations noted (from cover requirements calculated with and without these simplifying assumptions) were with particularly weak materials (CBR<2%) covered by a thin wearing course only. Bearing in mind the empirical nature of the technique and the relatively thicker wearing course layers encountered in mine haul roads, the adoption of the contact area and pressure assumptions are valid.

Contact area (A) of a tyre is given by;

$$A = \frac{LOAD}{TYRE\ PRESSURE} \qquad (m^2) \qquad [4.6]$$

from which follows the expression for contact radius.

The contact radius (r) is then;

$$r = \sqrt{\frac{A}{\pi}} \qquad \text{(m)} \quad [4.7]$$

The relationship developed by Turnbull and Ahlvin (1957) to describe the cover required (t) over a material of strength (CBR) subjected to a wheel load (P) is;

$$t = \sqrt{\frac{P}{55.8 \times CBR} - \frac{A}{\pi}} \qquad \text{(m)} \quad [4.8]$$

Equation [4.8] should only be applied where CBR values less that 12 are encountered, more recent research by Ahlvin et al (1971) in conjunction with work on multiple wheel groups, proposes the following relationship for cover thickness;

$$t = \sqrt{A}\left(-0.0481 - 1.1562\left(\log\frac{CBR}{p_e}\right) - 0.6414\left(\log\frac{CBR}{p_e}\right)^2 - 0.4730\left(\log\frac{CBR}{p_e}\right)^3\right) \qquad [4.9]$$

where p_e is defined as the equivalent tyre pressure at depth t given by;

$$p_e = \frac{ESWL}{A} \qquad [4.10]$$

When considering traffic volume, equations [4.8] and [4.9] can be rewritten to incorporate the repetition factor developed by Ahlvin et al (1971), a graphical relationship between repetition factor, number of repetitions and wheels in multiple configuration as given in Figure 4.9. This relationship is derived from consideration of aircraft wheel loads on asphalt surfaced pavements and the validity of its adoption for the design of gravel-surfaced mine haul roads for large haul trucks has not been ascertained. If a repetition factor is included, equation [4.11] represents the required CBR at a given depth (t) for the specific ESWL used whilst the revised equation [4.12] is solved iteratively.

$$CBR = \frac{ESWL}{55.8\left[\left(\frac{t}{\alpha}\right)^2 + \frac{A}{\pi}\right]} \qquad (\%) \quad [4.11]$$

$$t = \alpha\sqrt{A}\left(-0.0481 - 1.1562\left(\log\frac{CBR}{p_e}\right) - 0.6414\left(\log\frac{CBR}{p_e}\right)^2 - 0.4730\left(\log\frac{CBR}{p_e}\right)^3\right) \quad [4.12]$$

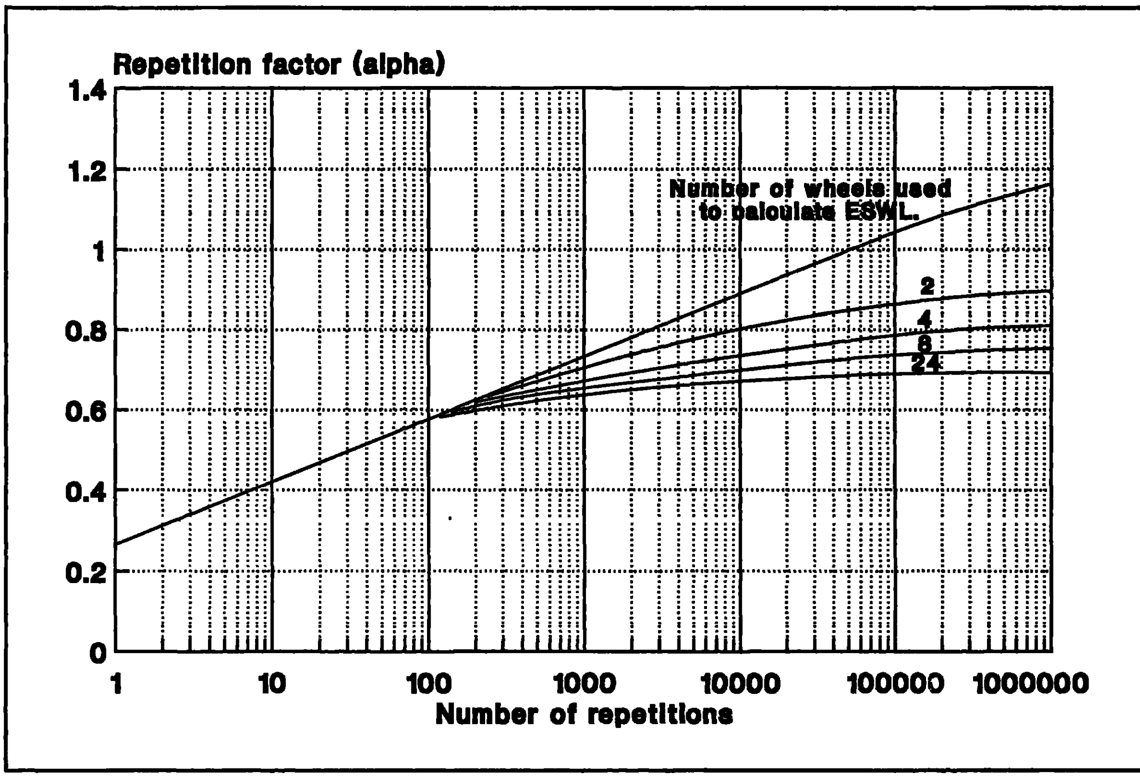


Figure 4.9 Load Repetition Factor (after Ahlvin et al, 1971).

The calculation of the ESWL for multiple wheels incorporates two conditions;

- the ESWL will have the same contact area (A) as the other wheels in the group
- and the maximum deflection generated by the ESWL will be equivalent to the maximum deflection generated by the group of wheels.

Following Foster and Ahlvin (1954) the deflection under a single wheel (W_s) is given by;

$$W_s = \frac{r_e}{E} b_s F_s \qquad \text{(m)} \quad [4.13]$$

Where r_s = contact radius for single wheel (m)
E = elastic modulus of pavement (MPa)
b_s = tyre pressure for single wheel (MPa)
F_s = deflection factor for single wheel

and for a group of wheels (W_d) similarly by;

$$W_d = \frac{r_d}{E} b_d F_d \qquad \text{(m)} \quad [4.14]$$

Following the conditions described above, equations [4.13] and [4.14] can be rewritten as;

$$W_s = W_d \;\; and \;\; r_s = r_d \qquad [4.15]$$

Equations [4.6] and [4.7] relate load and tyre pressure to contact area and combining with equation [4.13] gives;

$$P_s = \pi r_s^2 b_s \quad and \quad P_d = \pi r_d^2 b_d \qquad [4.16]$$

Equation [4.17] below represents this in terms of wheel loads and deflection factors for single and groups of wheels;

$$\frac{P_s}{P_d} = \frac{F_d}{F_s} \qquad [4.17]$$

Equivalent deflection values at specific depths for various horizontal locations are found graphically as shown in Figure 4.10 and these are used to determine the ESWL at various pavement depths.

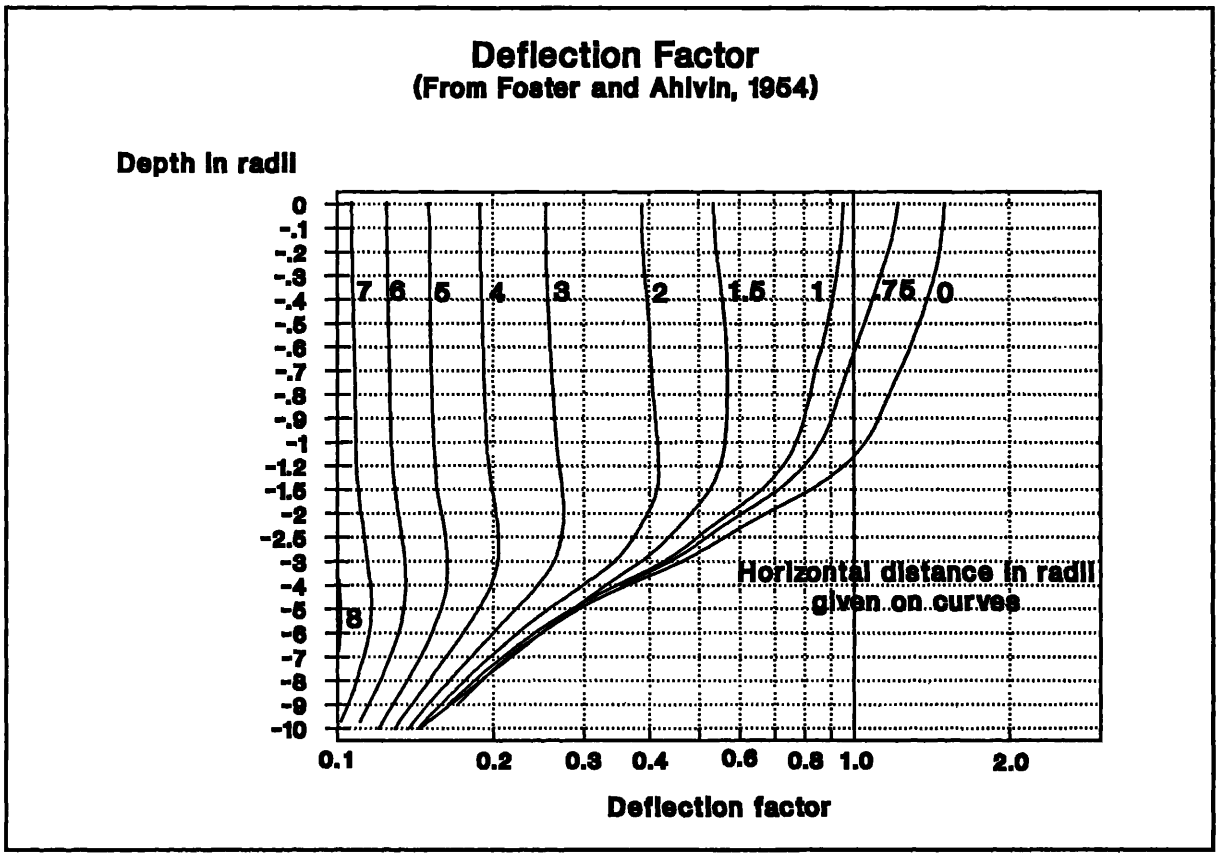


Figure 4.10 Deflection Factors for ESWL Determination (after Foster and Ahlvin, 1954).

The ESWL is calculated at a range of pavement depths from which the required CBR cover curve is constructed. The specific wheel grouping of a haul truck is reduced to four wheels by means of an equivalent single wheel load representing dual assemblies or axles and the deflections under four characteristic points recorded. These characteristic points are derived from consideration of the stresses generated in a uniform homogeneous pavement under the action of two sets of two wheels, specifically the increase in stress (and thus deflection) where stress fields overlap. With an equivalent single wheel load representing the dual assembly, the critical points (following Yoder and Witczak, 1975) occur either under the centre of one rear load (D) or at the centre of the rear axle (C). When the front axle interaction is considered, two additional critical points (A and B) are analysed in a position calculated in proportion to the fully laden axle weight distribution. This is represented schematically in Figure 4.11(a) whilst Figure 4.11(b) illustrates the corresponding layout of the wheel group of a Haulpak R170 truck with all dimensions normalised in terms of the tyre contact radius. The influence of each wheel in terms of deflection factor upon the characteristic point (A-D) chosen is summed and the maximum ESWL at that depth found

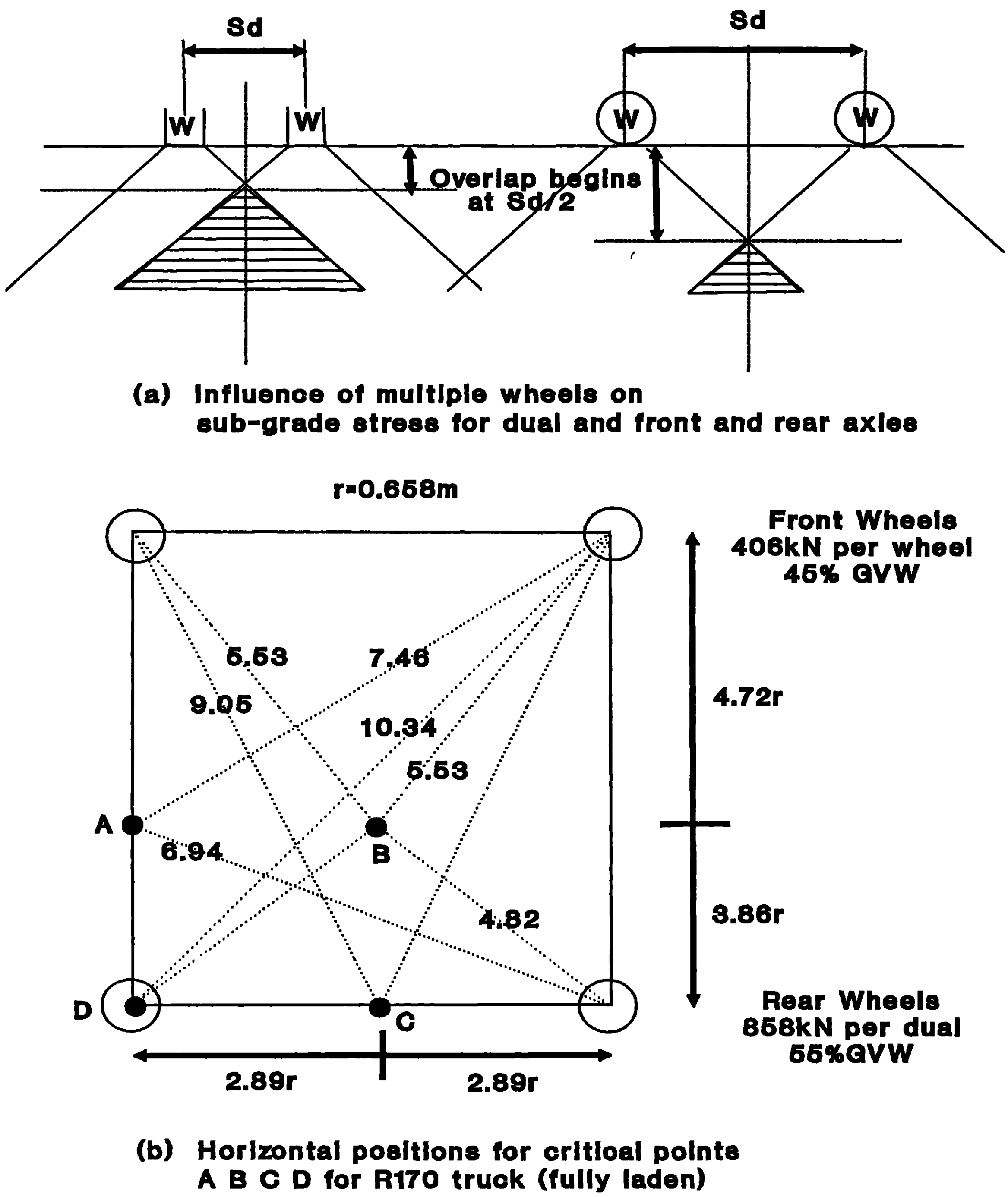


Figure 4.11 (a & b) Vertical Sub-grade Stress generated under a Group of 4 Wheels and (b) the Corresponding Critical Point Locations in Terms of Contact Radius (r).

from Equation [4.17]. The required cover for the maximum ESWL calculated at depth increment *r* is then calculated from equation [4.12]. As a basis for comparative analysis of the utility of the CBR method for haul road design, the CBR cover curve is calculated for the largest vehicle used on a particular mine site and compared with the actual design as determined by DCP analysis. Results for each mine site are summarised in the following sub-sections and given in full in Appendix C.

4.4.2 CBR Cover Curve Design - Kriel Colliery

Mine roads were historically designed for the 3-axle Cat 772 bottom dump truck and only comparatively recently have the larger 2-axle Euclid R170 rear dump trucks been introduced. It is thus instructive to generate separate cover curves for each vehicle to qualify any pavement under-design apparent with the use of R170 trucks.

Cat 772 Cover Curve

Two distinct drive groups for fully laden conditions must be considered;

(i) front wheel group (horse front and drive axles)

(ii) drive wheel group (horse drive and trailer rear axles)

Results of these two analyses are given in Appendix C. The possibility also exists of the horse group of wheels influencing the rear group of wheels in terms of deflection generated by the vehicle. Reducing the front group to an approximate equivalent and accepting the maximum contact radius to be associated with the rear group, the horizontal radii for the critical locations A-D normalised in terms of the contact radius are found to be large. With reference to Figure 4.10, it may be assumed that no influence is seen on deflections generated by the vehicle from combined front and rear groups. Figure 4.12 relates the horizontal radii for the combined front and rear groups.

Euclid R170 Cover Curve

The cover curve for the fully laden R170 truck is constructed for the front and rear wheel groups as outlined in the foregoing section, using the horizontal radius (r) associated with the

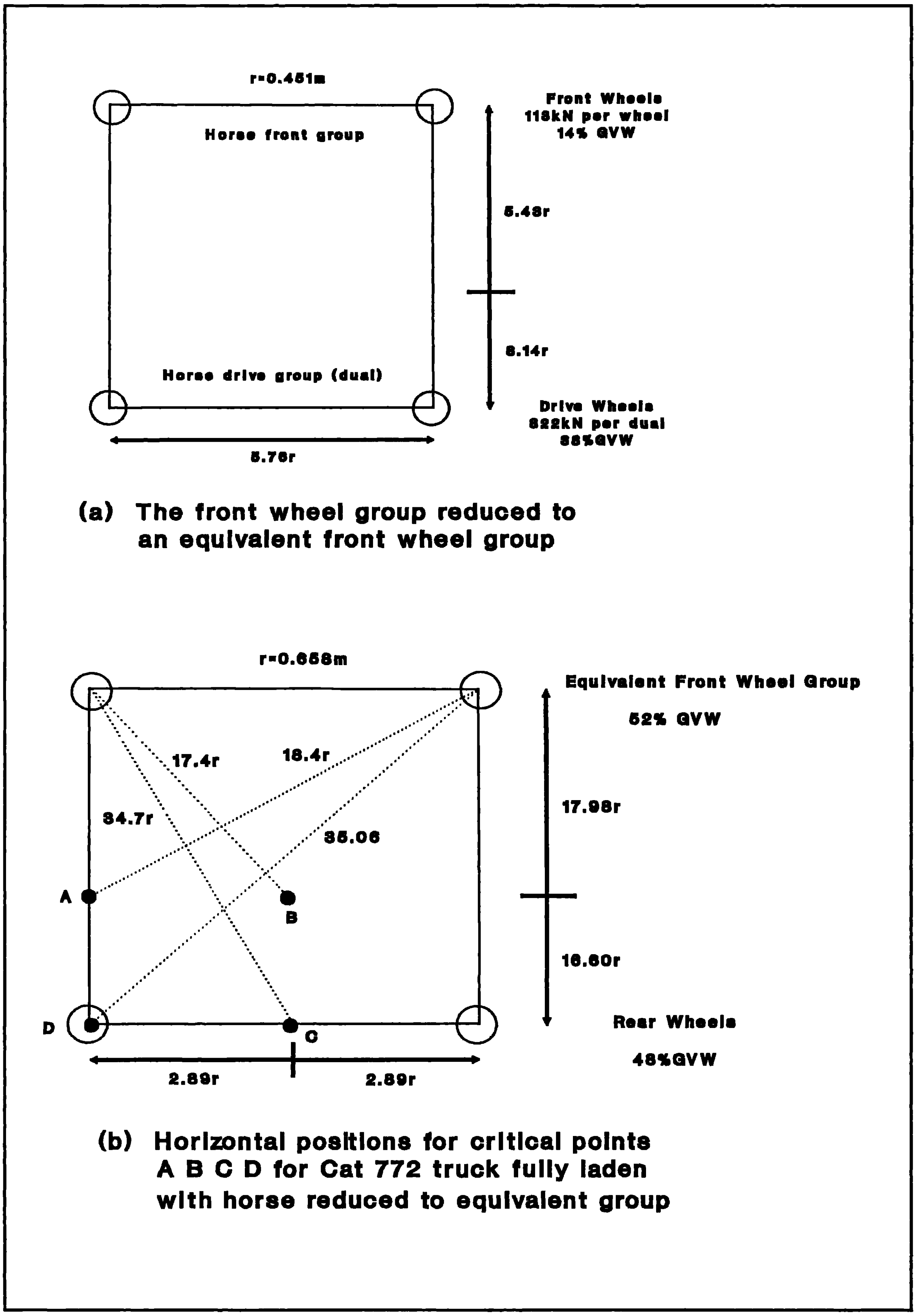


Figure 4.12 Horizontal Radii for Combined Front and Rear Wheel Groups, Cat 772 Truck.

rear group of wheels, as shown in Figure 4.11(b).

The DCP generated redefined layer strengths for each test site are given in Figure 4.13 together with the CBR cover curve for both vehicles considered. In all cases the design structural strengths exceed the minimum cover requirements predicted by the CBR calculation method. Site 1 layer 3 approaches the minimum cover requirements and the possibility exists that excessive vertical strains may develop in the layer due to overstressing. The extent to which this may lead to deformation in the sub-grade is not easily determined from the CBR data alone. The situation is ameliorated when the cover curve for the Cat 772 truck is considered.

4.4.3 CBR Cover Curve Design - Kromdraai Colliery

Mine roads were designed for the 2-axle Haulpak 630E rear dump truck and the required cover according to the CBR design method is calculated for fully laden conditions. The DCP generated redefined layer strengths for each test site are given in Figure 4.14 together with the CBR cover curve for the vehicle under consideration. The design structural strengths exceed the minimum cover requirements predicted by the CBR calculation method for sites 1 and 3. Site 2 layers 2 and 3 exhibit strengths below the CBR predicted minimum cover requirements and the possibility exists that excessive vertical strains may develop in these layers due to overstressing. Since road construction was not complete at the time of testing (September 1993), the placement of the final wearing course layer to design depth will have the effect of moving the redefined DCP layer strength profile down, thus effectively ensuring all layer strengths eventually exceed those predicted by the CBR design method.

4.4.4 CBR Cover Curve Design - New Vaal Colliery

Mine roads were designed for the 2-axle Komatsu HD 1600 M1 and Euclid R170 rear dump trucks, the former truck being used under fully laden conditions to derive the required cover according to the CBR design method. The DCP generated redefined layer strengths for each

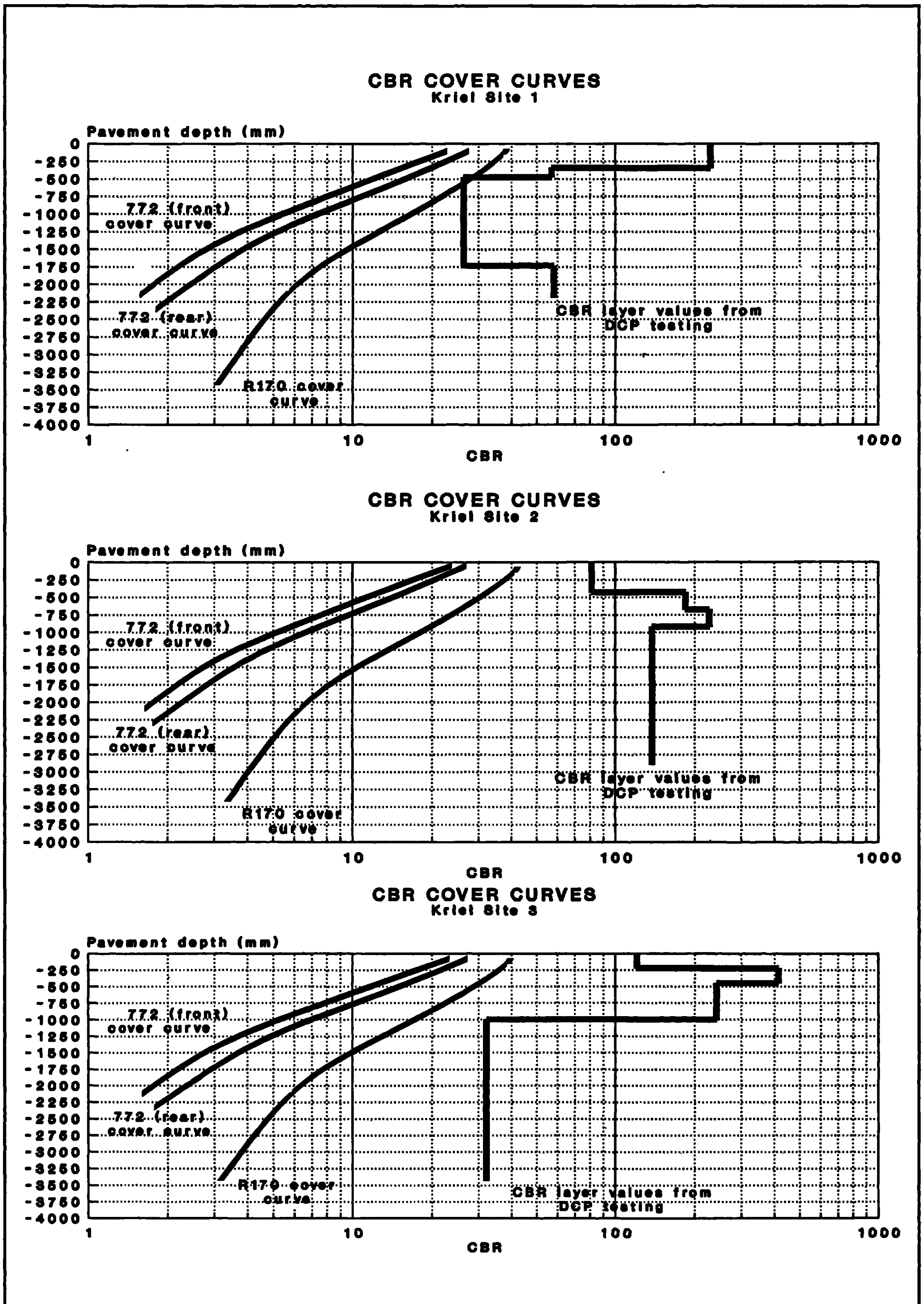


Figure 4.13 CBR Cover Curves for Kriel Colliery Sites 1, 2 and 3.

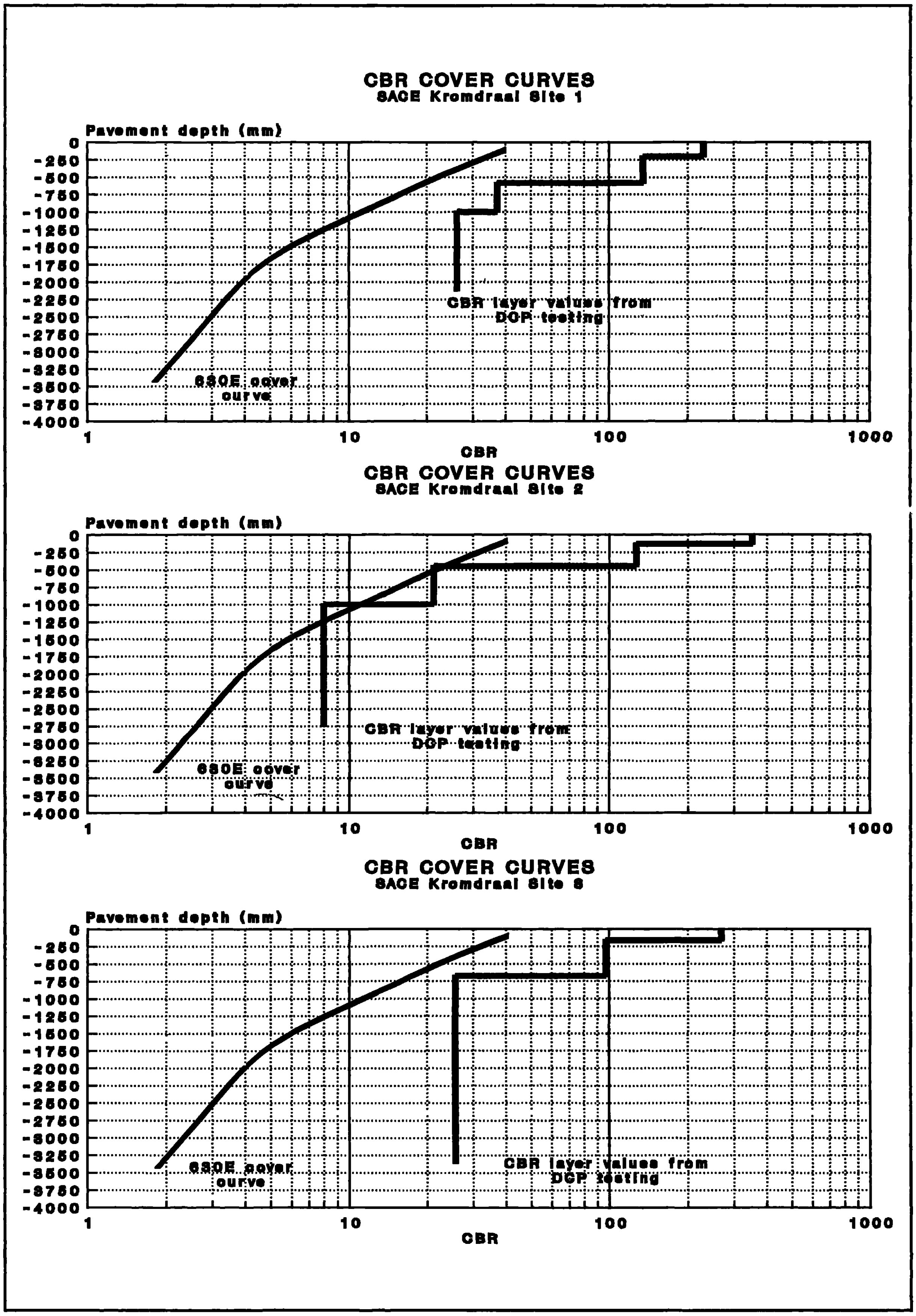


Figure 4.14 CBR Cover Curves for SACE Kromdraai Colliery Sites 1, 2 and 3

test site are given in Figure 4.15 together with the CBR cover curve for the vehicle considered. The design structural strengths are not exceeded by the CBR predicted minimum cover requirements at any site. Site 1 layer 4 and site 3 layer 3 exhibit strengths close to the CBR predicted minimum cover requirements and the possibility exists that excessive vertical strains may develop in these layers due to overstressing. However, the extent to which this may lead to deformation of the sub-grade is not easily determined from the CBR data alone.

4.5 Summary of Results for CBR Cover Curve Design

The CBR method has been widely applied to the design of surface mine haul roads in which untreated materials are used. In essence, it relates sub-base thickness requirements to sub-grade bearing capacity, thereby eliminating overstressing and consequent deformation of the sub-grade due to axle loading.

Although the CBR method is a simple and straight forward design method based on and improved by considerable practical experience, numerous disadvantages exist when applying the method to mine haul road design problems: The method has its base in Boussinesq's single semi-infinite layer theory which assumes a constant elastic modulus for the material (sub-base). Mine haul road structures consist of numerous layers of differing material each with its own specific elastic and other properties. More specifically, the CBR method was based on empirical results relating to the design of asphalt-surfaced airfield pavements for wheel-gear loads upto 4 400kN for a C5A aircraft. When aggregate-surfaced mine haul roads are considered in conjunction with stabilised bases, albeit at similar load levels, the same approach is of questionable validity. The graphical relationship proposed by Ahlvin et al (1971) in conjunction with the modified CBR design technique to accomodate the effect of traffic repetitions may also therefore not be applicable to haul road structural design. Simple extrapolation of these empirical design criteria to accommodate higher axle loads upon very different pavement construction materials can lead to serious errors of under- or over-design.

The deficiencies inherent in the development of the CBR design method militate against using

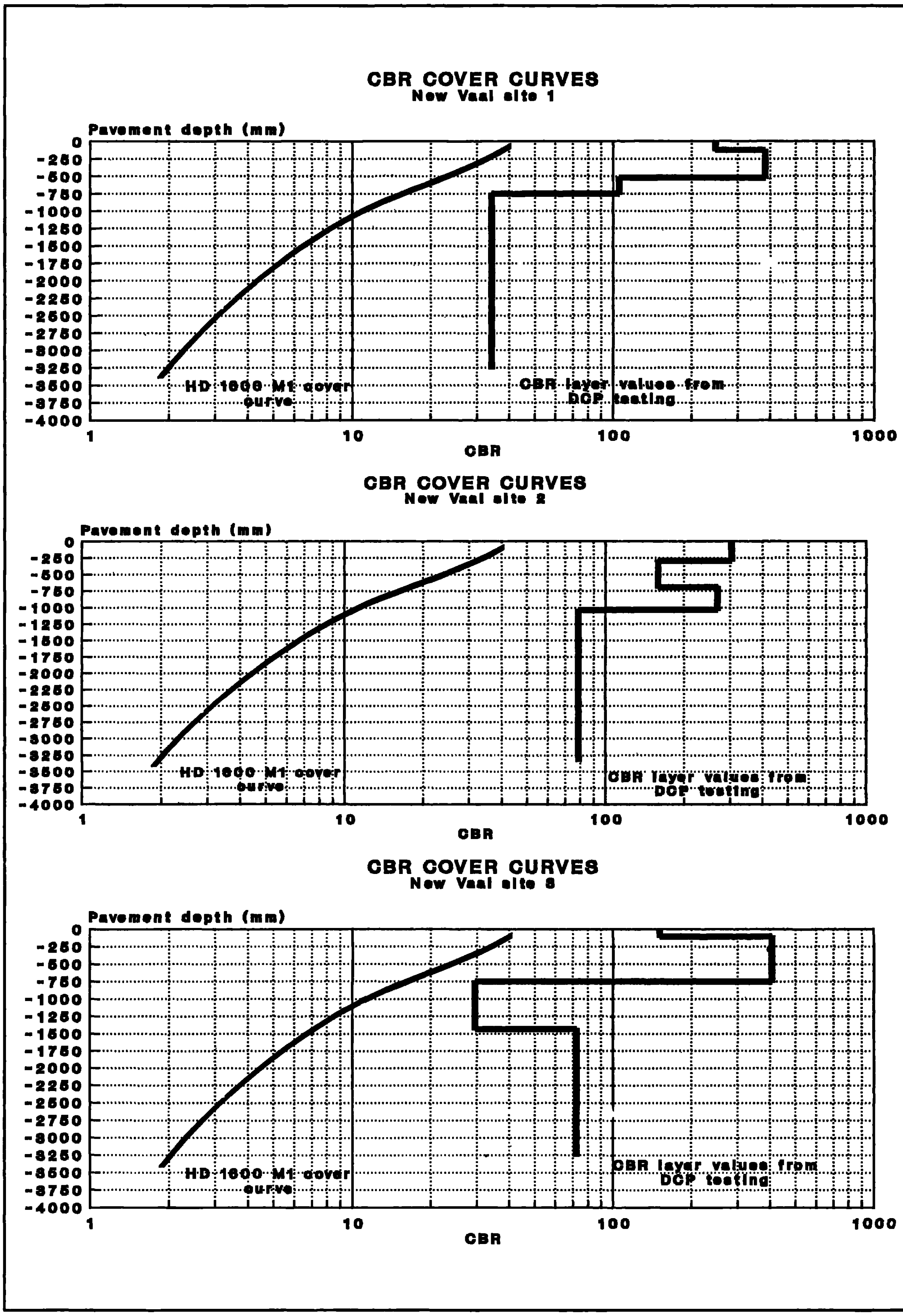


Figure 4.15 CBR Cover Curves for New Vaal Colliery Sites 1, 2 and 3.

the techniques for the structural design of mine haul roads. When the results of the DCP redefined layer strengths are analysed in conjunction with the CBR cover curves generated, it would appear that the method, when applied judiciously, can be used to determine safe (total) cover over in-situ materials, although the extent of over or under design associated with the method cannot be qualified. The method is thus exclusively recommended to design cases where no surface layers exist above standard gravel bases. Where cemented or stabilised layers are included in the design, or where the optimal structural design is sought, due to the very different properties of the layer in comparison to normal roadbuilding gravels, other design techniques should be employed which can account for the different material properties and more accurately predict their performance.

CHAPTER 5
MECHANISTIC ANALYSIS AND QUANTIFICATION OF EXISTING PAVEMENT STRUCTURAL DESIGNS

5.1 Introduction

This chapter addresses the mechanistic analysis and quantification of existing haul road structural designs. The fundamentals of the mechanistic design procedure are introduced and the benefits the method accrues over purely empirical approaches are discussed. Pavement deflection profiles generated from Multi-depth Deflectometer installations in mine pavements are then analysed with the aid of multi-layer pavement elastic models and the ELSYM5A (1985) computer program. The mechanistic-empirical design process is then introduced, by means of which the results of the multi-layer elastic analyses are used to deduce acceptable design criteria for haul road structural design.

5.2 Fundamentals of Mechanistic Design

The mechanistic approach to pavement engineering involves the application of physics to determine the reaction of the pavement structure to loading. Of prime importance is the extent to which the structure distributes vehicle loads to the underlying in-situ material. Weak pavement structures concentrate the load over a smaller area of the sub-grade than strong pavements as shown schematically in Figure 5.1, resulting in higher stresses in the sub-grade. In order to quantify how the load is being distributed, certain fundamental properties of the materials comprising the structure must be determined along with layer thickness and load characteristics. The mechanistic component relates to the determination of stresses, strains and deflections within the pavement layers through the use of layered elastic analysis.

Empirical design criteria are to some extent a requirement of all structural design techniques. Whilst the CBR based approach is entirely empirical and therefore subject to data characteristic limitations, the mechanistic approach, although including an empirical

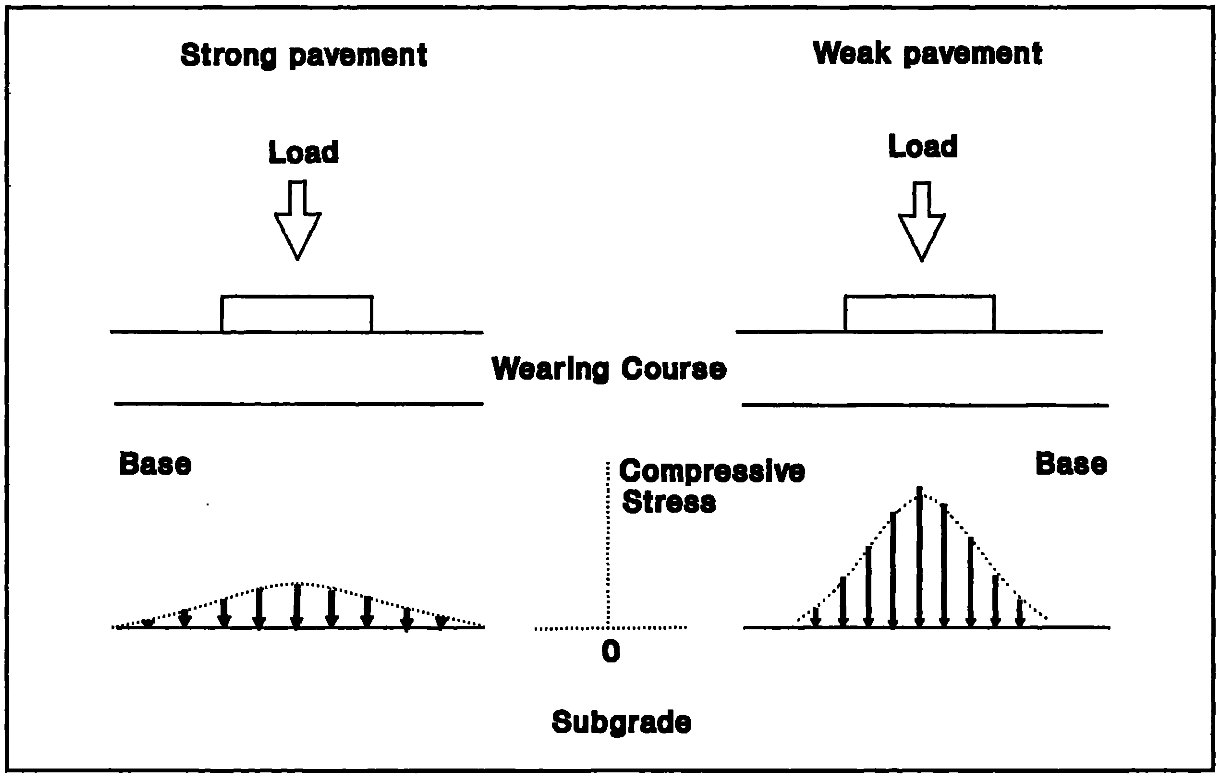


Figure 5.1 Load Distribution Characteristics of a Strong versus Weak Pavement

component, relies largely on mechanistically derived data to which empirical procedures are applied, therefore extending the functionality of the technique. Typical benefits of the mechanistic-empirical approach when applied to haul road design are;

(i) The ability to accommodate changing loads and analyse their impact on pavement structural performance in terms of the strains developed in each layer

(ii) The ability to utilise available construction materials in a more efficient manner by evaluating excessive vertical strains that be be induced in poorer quality materials

(iii) The ability to analyse the effect of alternative construction materials on the pavement structure and modify the design to accommodate these materials within the design limiting criteria

(iv) More reliable performance predictions for multi-layer structures incorporating various material qualities

(v) Use of material properties in the design process which are more closely related to field performance of the structure, particularly the elastic reponse of the pavement

(vi) An improved definition of existing pavement layer properties.

The basic theory from which the procedure is developed is attributable to Boussinesq. Equations were presented from which stress, deformation and deflections could be calculated in a homogeneous, isotropic linear elastic half space, subject to point loading. In the early 1900's Love developed extensions to the basic equations to account for circular loads whilst Westergaard later modified the equations for no deflection in the uppermost layer. Latterly Timoshenko developed the general theory for a linear elastic system upon which Burmister advanced a solution for 2 and 3 layer systems using numerical integration. The equal deflection criteria for the determination of ESWL described in section 4.3.1 and developed by Foster and Ahlvin is derived from Boussinesq's solution, but with the application of circular loads. Numerical integration techniques for the direct solution of multi-layer multi-load problems are now widely available with the advent of microcomputers.

A simple and convenient method to assess the structural integrity of pavements is to apply a load and measure the resulting depth deflection profile. The Multi-depth Deflectometer as described in section 3.2.1.3 can be used for this purpose, in which an array of 6 Linear voltage differential transducers (LVDTs) are used to determine the pavement layer deflections resulting from an applied load. A typical depth-deflection profile is given in Figure 5.2 from which it is seen that the larger deflections occur towards the top of the structure. These deflections are used together with a multi-layer analysis program to determine the layer effective elastic moduli, stresses and strains by means of which the response of the structure may be characterised. These stresses and strains are used in conjunction with empirical limiting fatigue or distress values and relationships to evaluate structural performance of the pavement and, if necessary, to evaluate the efficacy of corrective measures.

5.2.1 Layered Elastic Systems

Much of the structural deterioration of a pavement is attributable to the stresses or strains developed in individual pavement layers. Vertical strains in the top of sub-base and sub-grade layers are associated with rutting and deformation whilst strains in upper stabilised

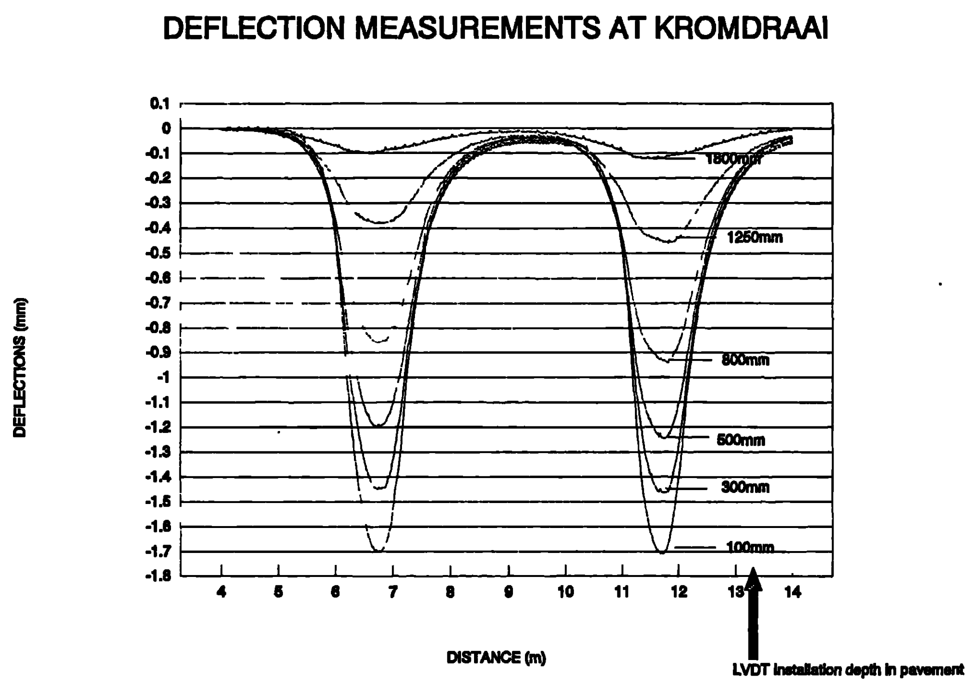


Figure 5.2 Typical Depth-deflection Profile Generated From a MDD Array.

layers with cracking. To determine the layer response to an applied load, it was necessary to use layered elastic models and a back-calculation approach in which actual pavement deflections were compared with those calculated in the model pavement structure for a particular modulus of elasticity. The ELSYM5A (1985) program is used for this purpose.

The effective modulus of elasticity (E_{eff}) and Poisson's ratio (μ) define the material properties required for computing the stresses (deviator σ_d and sum of principals Θ) and strains (vertical ϵ_v and horizontal ϵ_h) in a pavement structure. In addition to the material properties, layer thickness is also specified, in this case with reference to the DCP derived redefined layer structural thickness data given in Appendix B. For computational purposes, the layers are assumed to extend infinitely in the horizontal direction and the lowest pavement layer, extending from a point where the MDD recorded deflections are extrapolated to zero, to be infinite in depth and assigned a high elastic modulus to account for the observed stiff layer with zero deflection. It is also assumed that material behaviour is perfectly linearly elastic, homogeneous and isotropic.

The applied load is calculated according to the mass of the vehicle and the axle load distributions given in Tables 3.3, 4 and 5, together with tyre pressure, to calculate the contact stress. The assumption is made that the area of the applied load approximates to a circle which is valid except at very shallow pavement depths. Figure 5.3 summarises the layered elastic model and data requirements.

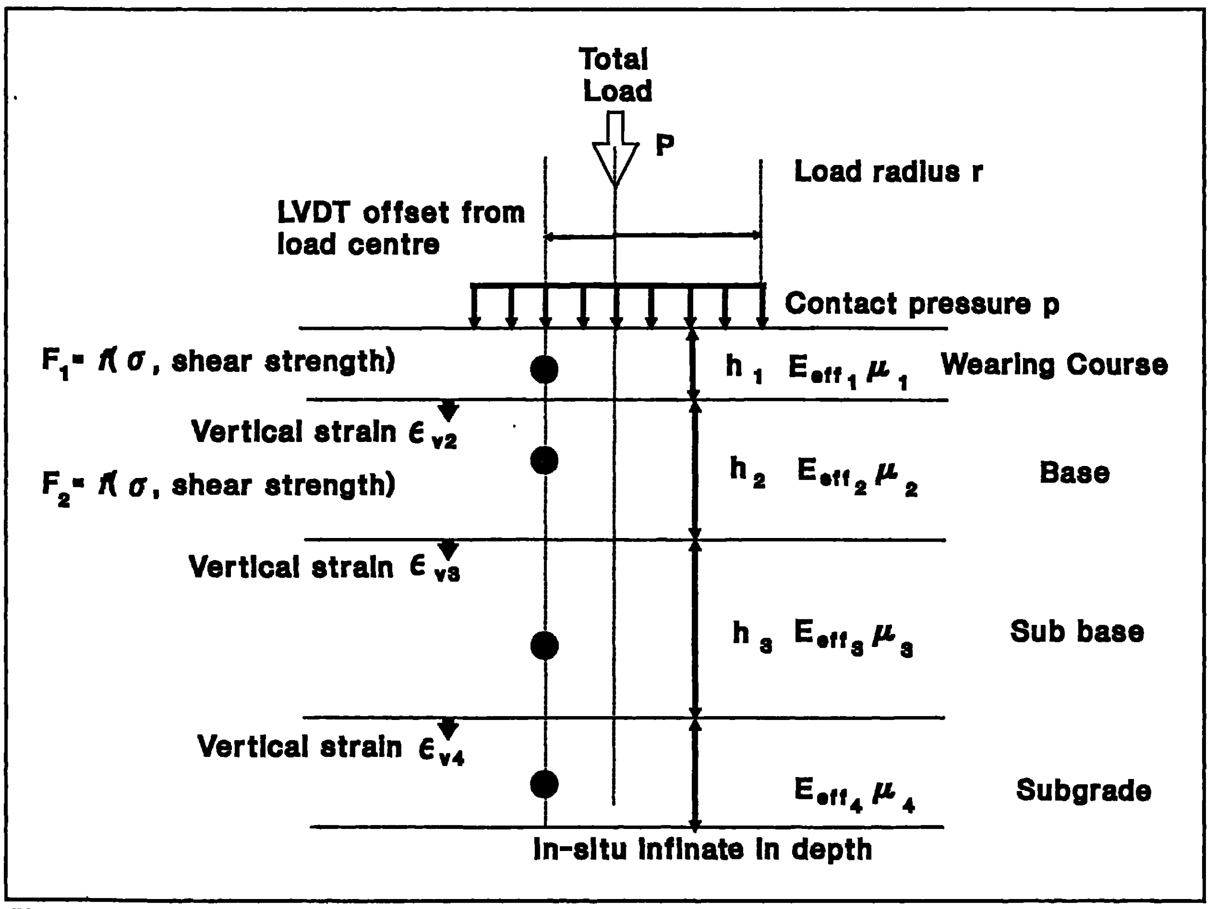


Figure 5.3 Layered Elastic Pavement Model for Use with MDD Data.

5.3 Mechanistic-Empirical Design Process

The deflections generated in each pavement layer due to the applied load are used to back-calculate an effective elastic modulus which satisfies the measured deflections recorded in each layer. The elastic modulus represents a constant ratio of stress and strain as presented in equation [5.1].

$$E_{eff} = \frac{\sigma}{\varepsilon} \quad \text{and} \quad \varepsilon = \frac{\Delta l}{l}$$

where σ = stress (MPa) in layer [5.1]
ε = strain in layer
Δl = deflection in layer
l = layer thickness

Poisson's ratio relates the ratio of transverse to vertical strains and is required for elastic layer modelling with the ELSYM5A program. Since it is particularly difficult to generate reliable values for Poisson's ratio from laboratory tests, an assumed value is used. It is believed that multi-layer elastic analyses are relatively insensitive to small variations in this value. A value of 0,35 is suggested by Maree and Freeme (1981) to be representative of most granular materials, although saturated materials can exhibit a value of 0,5.

The solution technique adopted with the ELSYM5A program involves the manual iteration from some assumed seed moduli for each layer until calculated deflections match those measured by the LVDTs. The seed value used for the effective elastic moduli is derived from the DCP testing data reported in Chapter 4.2. Little work has been done to correlate DCP results with effective elastic moduli although De Beer (1991, 1992) has proposed a tentative empirical relationship based on a 40kN dual wheel load (520kPa contact stress) which is illustrated in Figure 5.4. The relationship may be expressed mathematically as given in equation [5.2] with associated standard error of estimate of 0,209 and R^2=76% for a penetration rate of 0,63 to 25mm per blow (CBR from 7% to 380%).

$$\log(E_{eff}) = 3{,}04758 - 1.06166(\log(DN)) \qquad [5.2]$$

This relationship is used initially as a seed value from which to commence the manual iteration. It remains to be seen whether this relationship holds true at the load and stress levels encountered on mine haul roads. Other empirical relationships exist by which the seed moduli may be sought, including the Shell, WES, TRRL and Danish Road Laboratory methods (Federal Highway Administration, 1994). These are limited in their applicability to CBR ranges of 1% to 20% only.

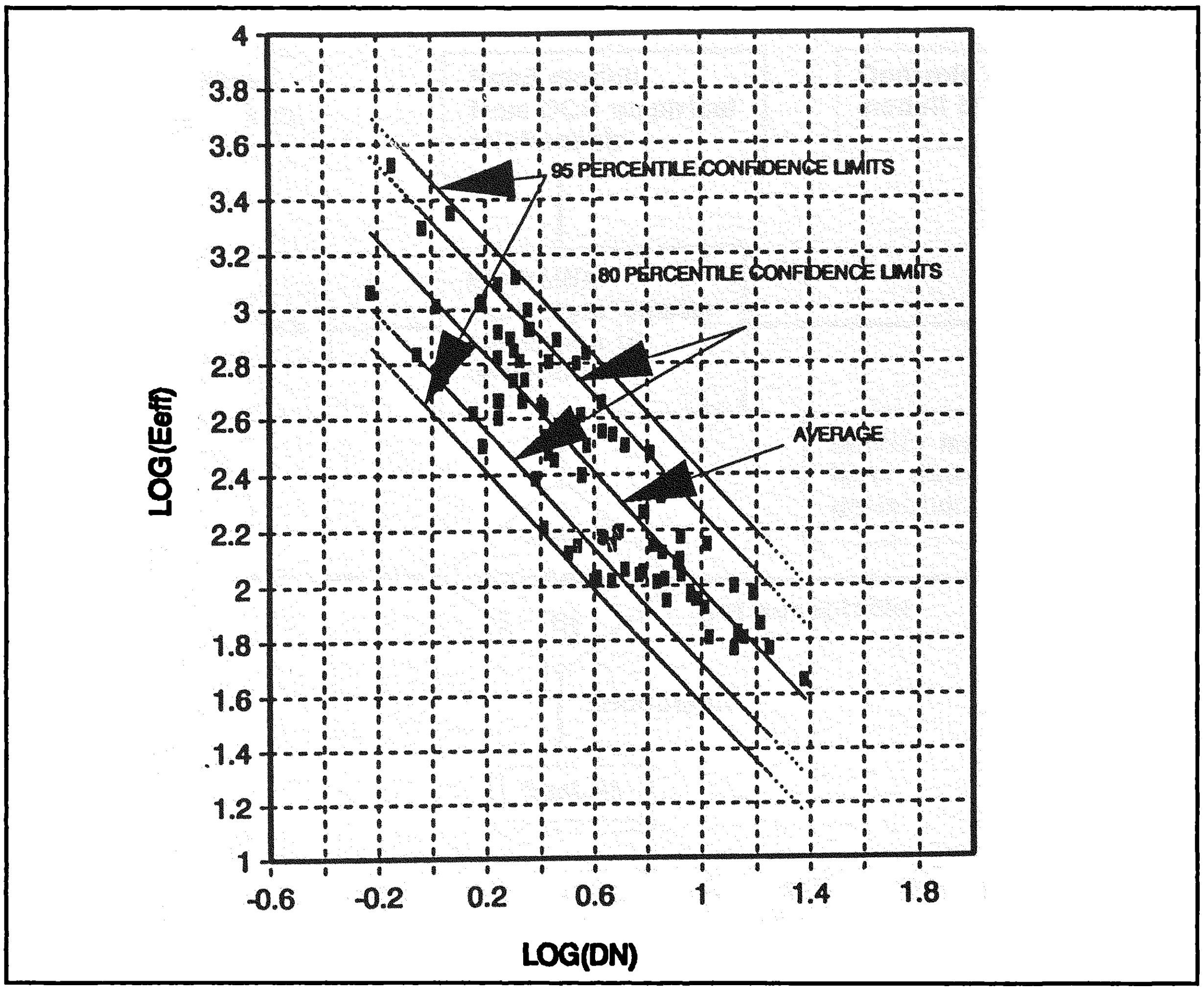


Figure 5.4 Tentative Empirical Relationship Between Effective Elastic Modulus (E_{eff}) and DCP Penetration Rate (DN) for a 40kN Dual Wheel Load(after De Beer, 1991)

The goodness of fit is determined for a particular LVDT (usually located centrally within the layer) to within 2% of the actual recorded deflection. The procedure is illustrated in Figure 5.5. Once individual layer moduli are determined, stresses and strains are then determined with ELSYM5A and compared to established design criteria to verify whether critical stresses or strains have been exceeded. Little published data exists concerning established design criteria for haul roads. The most tractable approach is thus to identify those damage parameters applied in the design of pavements subject to standard axle loadings and by means of categorising haul road test section structural performance, deduce acceptable design criteria for haul road structural design. In the case of haul road structural design and analysis, three distinct design criteria may be adopted from conventional pavement design. Table 5.1 appertains to the criteria associated with the pavement structural layers.

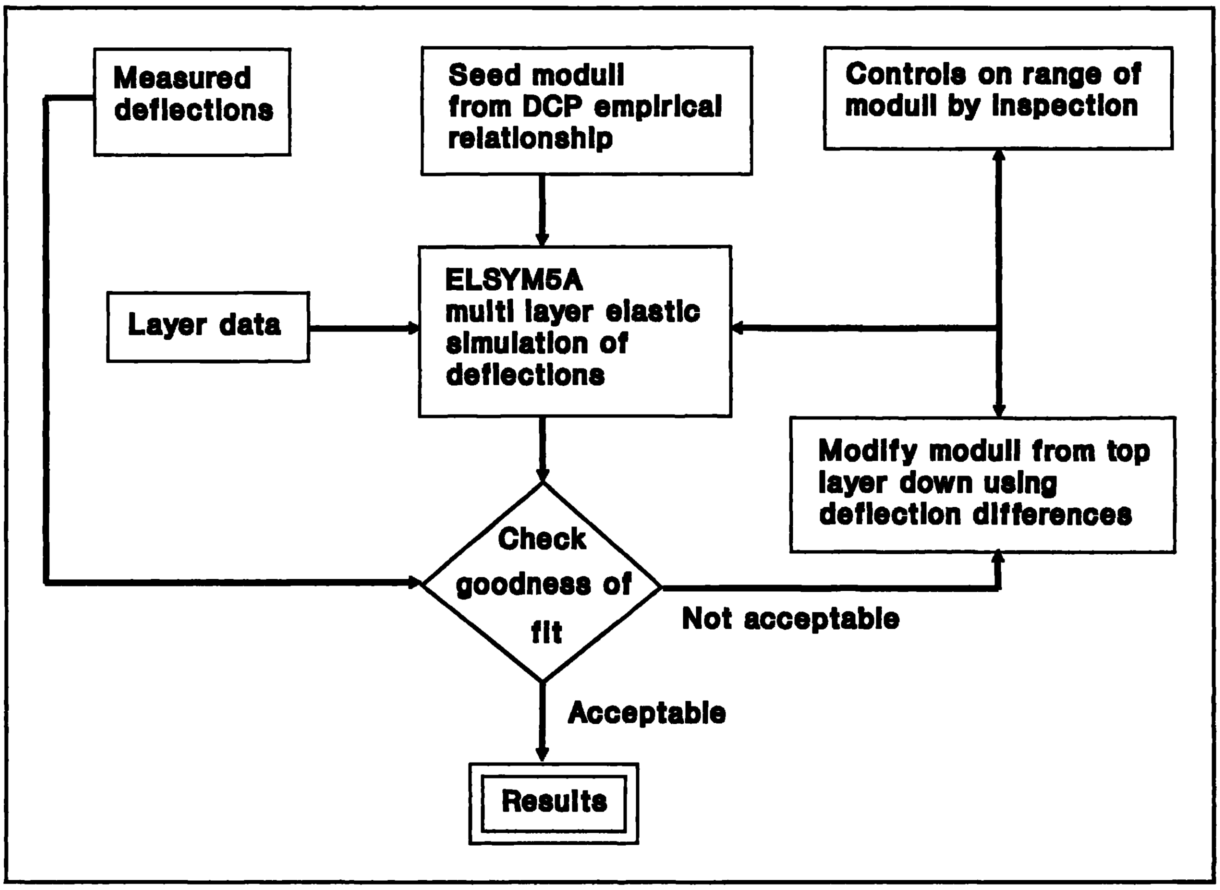


Figure 5.5 Manual Iteration Procedure used with ELSYM5A Program (after Lytton, 1989)

Table 5.1 Design Criteria Applied to Haul Road Pavement Layers (after De Beer, 1992)

LAYER	DAMAGE PARAMETER	DESIGN CRITERION
1	Stress state (σ_1, σ_3)	Safety factor (F) where F $= f(\sigma$, shear strength) Stress sensitivity
2	Stress state (σ_1, σ_3) Vertical compressive strain	Safety factor (F) where F $= f(\sigma$, shear strength) ϵ_v Stress sensitivity
3	Vertical compressive strain	ϵ_v Stress sensitivity
4	Vertical compressive strain	ϵ_v Stress sensitivity

Safety Factor

Granular materials exhibit distress through cumulative permanent deformation or inadequate stability. Both forms of distress are related to the ultimate shear strength of the material and to prohibit shear failure or excessive gradual shear deformation in the layer, traffic generated shear stresses must be limited. The ultimate shear strength of the layer can be calculated from the maximum single load shear strength, expressed in terms of the Mohr-Coulomb strength parameters c (cohesion) and Φ (angle of internal friction).

The safety factor at any point in the layer can be defined following Maree (1978) as;

$$F = \frac{\text{Maximum safe shear stress}}{\text{working shear stress}} \qquad [5.3]$$

from which equation [5.4] follows;

$$F = \frac{2Kc\tan\left(45+\frac{\Phi}{2}\right)+\sigma_3\left|K\tan^2\left(45+\frac{\Phi}{2}\right)-1\right|}{|\sigma_1-\sigma_3|} \qquad [5.4]$$

where σ_1 and σ_3	=	calculated major and minor principal stresses acting at a point in the layer. (Geomechanics sign convention adopted)
c and Φ	=	Mohr-Coulomb strength parameters cohesion (kPa) and angle of internal friction (degrees)
K	=	Constant; 0,6 for highly saturated materials, 0,95 for normal conditions
σ_3	=	Minor principal stresses

Equation [5.4] can be rewritten to accommodate published values for friction and cohesion term components applicable to the particular granular material. In this case;

$$F = \frac{(\text{c-term}) + \sigma_3(\phi\text{-term})}{\sigma_d} \qquad [5.5]$$

Published c and Φ term components (Maree and Freeme, 1981) for dry base quality gravel (G4) are generally applicable for materials used in haul road construction, in this case 223 and 5,50 respectively. The shear strength c and Φ terms increase with increasing quality of the road building material and a reduction in moisture component thereof. Safety factors vary widely with depth within a layer, typically between compressive and tensile conditions. In this analysis, safety factors are calculated under single or at the centre of dual wheel assemblies at the mid-depth of the layer, following Maree (1978). Minimum safety factor values are available for various levels of equivalent traffic (E80 axle repetitions) for various categories of public roads. Owing to the uncertainty surrounding the load equivalency factor and equivalent damage attributable to ultra-heavy axle loads (between 600 and 300 000 passes of a standard E80 axle), extrapolation of these recommended safety factor values is unreliable and recourse must be made to categorisation of performance to deduce limiting safety factor values.

Elastic Vertical (Compressive) Strain

For paved roads, limitations are placed on the permissible compressive vertical elastic strains at the top of subgrade layers to prevent rutting and subsequent deformation of the road surface. Limiting the rut depth for unpaved roads is valid and in addition penetration of the upper construction layers into the subgrade should be avoided. In a similar manner, the Asphalt Institute subgrade design criteria for flexible airport pavements establishes permissible subgrade strain values for different load repetitions and subgrade moduli (Asphalt Institute, 1973), as does the Federal Aviation Administration (Brown and Rice, 1971).

Four characteristics of an unpaved road that influence the magnitude of vertical subgrade strains under the application of a constant wheel load may be identified;

(i) Resilient modulus of wearing course material

(ii) Wearing course layer thickness

(iii) Subgrade resilient modulus

(iv) Wander width

In the case of lateral wander width, although the depth of rutting that results from a given level of vertical strain is influenced by wander width, the operational practice observed on strip mine haul roads tends more to channelised (haul truck) traffic. This arises primarily from the left-hand drive configuration of the trucks and the various traffic speeds on the road, predictability being important for safe overtaking maneuvers.

The design criteria for the layers below the wearing course is that of horizontal tensile or vertical compressive strain depending on whether stabilised layers are used or not. These relate to the failure criteria of fatigue cracking of stabilised layers and rut initiation in the subgrade (respectively). Analogous to the safety factor design criteria, no published data exist relating the limiting values for strains in a haul road associated with adequate structural performance. Recourse must be made to categorisation of performance to deduce limiting vertical strain values, taking cognisance of the characteristics and limiting strain values suggested above.

The performance of stabilised layers included in the structural design of haul roads is not considered here since similar structural performance levels may be obtained without the use of (relatively expensive) stabilisation techniques. Additionally, only one mine site incorporated a stabilised layer in the design and thus no comparative conclusions may be drawn concerning the relative efficacy of the various design options available with stabilised layers.

Stress Sensitivity

Many unbound granular materials are stress sensitive with moduli significantly affected by stress level. Granular materials will often exhibit stress-stiffening behaviour with the modulus increasing with increased stress level according to the general relationship given in equation [5.6]. Fine grained materials exhibit the converse, where modulus decreases with increasing stress level. Equation [5.7] represents this behaviour. When considering the structural design of a pavement it is important to categorise this stress dependant behaviour since departures from anticipated behaviour (especially predicted stress-hardening in granular materials) may lead to under design.

Generally for granular materials;

$$E = k_1 \theta^{k_2} \qquad [5.6]$$

where k_1, k_2 = constants
θ = sum of principle stresses

Generally for cohesive materials;

$$E = k_3 \sigma_d^{\;k_4} \qquad [5.7]$$

where k_3, k_4 = constants
σ_d = deviator stress

The stress sensitivity of the materials comprising each mine test site pavement layer are determined graphically from the results of the ELSYM5A analysis for the various loads applied. By plotting the variation of either the deviator stress (σ_d) or the sum of principal stresses (Θ) against the effective elastic modulus of each pavement layer material, any stress-stiffening or -softening can be identified.

5.4 Multi-depth-deflectometer Results

Results of the MDD installations at each mine site are given in Appendix D. A typical result is given in Figure 5.6 showing the average pavement deflection associated with a particular vehicle. For each vehicle axle test, average deflection values were calculated by inspection on the basis of load offset from the MDD array vertical axis.

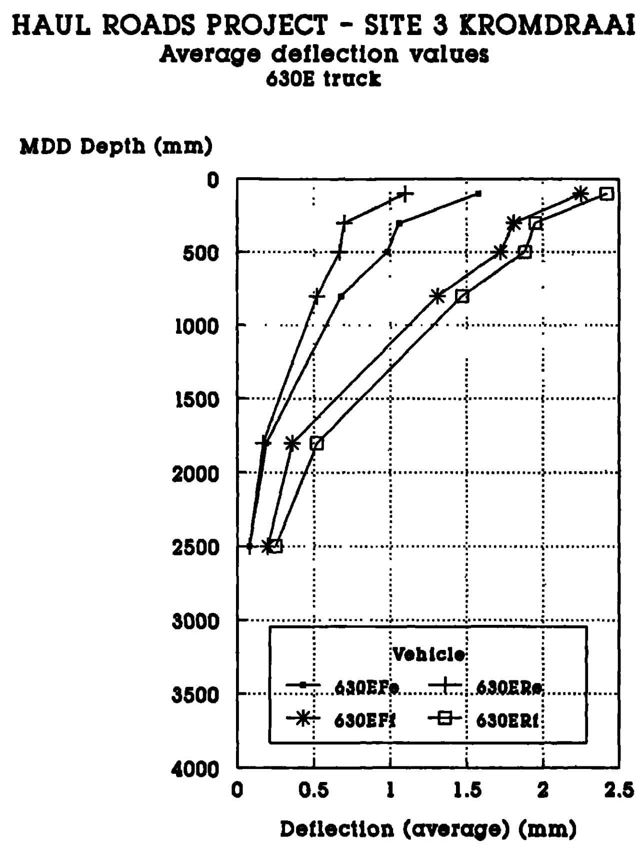


Figure 5.6 Typical MDD Derived Vehicle Deflection Profile.

The top of the model semi-infinite lowest layer is determined by extrapolating deflections to zero. This indicates the depth at which no load induced stress or strain is felt in the subgrade. With reference to Figures 4.5, 6 and 8, it may be seen that this depth varies according to the structural design used. Additionally, the top of the layer is defined for the largest applied load encountered at the particular mine site. Since no deflections are felt below this level, a high modulus value is ascribed to this material to simulate a rigid base. Additionally, high water tables (as evidenced during MDD installation and cone penetrometer probing) can also be reconciled with the inclusion of a stiff layer as a result of pore pressure increases in response to an applied (transient) load. For the mine sites investigated several exhibited saturated material deeper in the road stucture. Whilst this may appear favourable in terms of subgrade deformation, fluctuations in water table levels and the application of slow moving heavy loads may give rise to incidences of deformation and road structural failure. Nevertheless, the analysis serves to provide original data confirming the depths at which no load induced strains are felt for the ultra-heavy loads applied by mine haul trucks.

5.5 Haul Road Structural Performance Classification

As a precursor to the analysis of the structural performance of haul roads and the derivation of limiting design criteria for safety factor and vertical compressive subgrade strain, a classification of haul road structural performance was required to indicate in broad terms the adequacy of the various designs encountered. This was achieved by assigning each mine test site an index on a scale of 1-10 representing poor to excellent structural performance, together with a short summary of the structural defects observed or reported by mine personnel. In addition, the maximum deflection recorded in the structure was depicted for each site for dual rear wheel loads ranging from 429-439kN as an aid to classification. Figure 5.7 illustrates these data.

5.5.1 Results of Mechanistic Analysis - Kriel Colliery

Results are presented in Appendix D1 for all Kriel Colliery site mechanistic analyses.

<u>Site 1</u>

The pavement construction at this site consists of approximately 5m of fill under the pavement. Structural thickness is 1700mm, consisting of 320mm wearing course, 140mm base and 1240mm sub-base. The fill material is modelled to a depth of 2100mm, below which no deflections were measured. Structural performance according to Figure 5.7 is very poor and mine personnel report that excessive maintenance is required in this area. The pavement is seen to deform both vertically and horizontally due to the combined failure of the road shoulders and running surface under the action of high axle loads. The DCP analysis provides some insight into structural performance in terms of the pavement balance (Table 4.2) in which it is seen that this site is an averagely balanced shallow structure, susceptible to failure in the upper layers. CBR values for the layers range from 228% in layer 1 to 27% in layer 3.

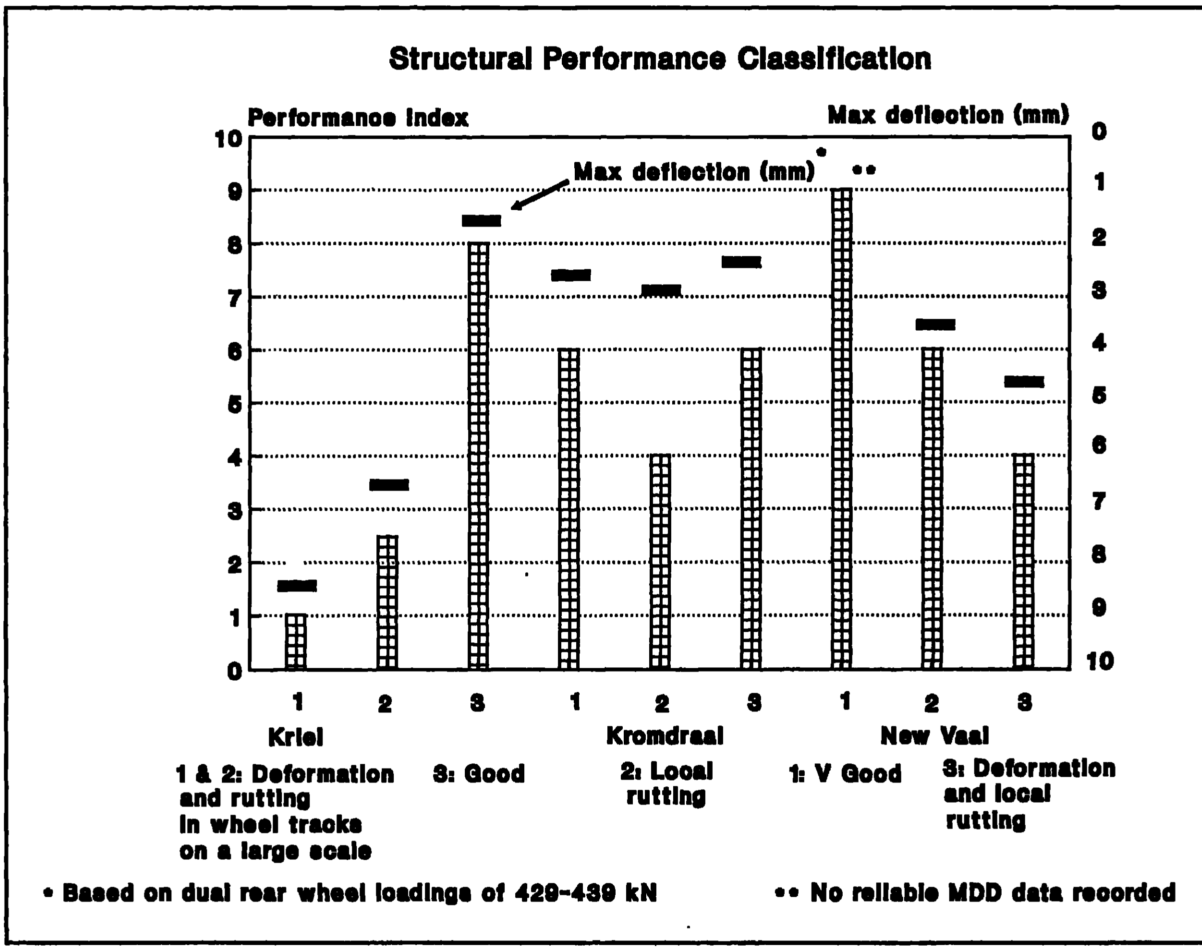


Figure 5.7 Structural Classification of Mine Haul Road Test Sites

With regard to the modelling of deflections generated by the MDD installation, a good fit was seen for most layers except layer 1 uppermost module. The effective elastic moduli for layer 1 could be questioned, especially if non-linear behaviour is present as a result of an impure granular material. This was evidenced at the site by cracking of the wearing course under the shear action of the wheel loads. This implies the material has a high plasticity index and thus deviates from a true granular material. The effective elastic modulus adopted for this layer was highly variable (200-550MPa) but accomodated repeatable modulus values and closer agreement between measured and calculated deflections lower in the pavement.

The factor of safety (FOS) design criterion reveals that the wearing course has a minimum FOS of 5 whilst the base and FOS of approximately -3 at the midth depth positions chosen. These values are indicative of both layers bending and hence a stress reversal from compressive to tensile deeper in the structure. In layers 2, 3 and 4 the design criterion is that of vertical strain. It is clear that layer 3 is subjected to excessive strain whilst layers 2 and 4 proportionately less. The excessive vertical displacement experienced at this site may then be attributable to deformation in these layers.

Regarding the propensity of the various pavement layers to stress harden or soften, plots are presented of effective elastic modulus against deviator and sum of principal stresses (respectively) to ascertain if such effects are seen. Stress softening of layer 2 material is evident, reducing its strength under the action of increased loads. A granular pavement generally exhibits stress hardening and thus the material comprising layer 2 does not have a pure granular structure. A plasticity index value for the layer of 12-15 as opposed to less than 8 for granular materials confirms the observed behaviour. No stress hardening effects are seen.

If the CBR cover curve design criteria (section 4.4.2) are compared with the results of the mechanistic analysis it is seen that the outcome of the CBR technique is under-design, specifically in terms of the excessive vertical strains seen in layers 3 and 4. This is seen by the approach of the top of layer 3 to the minimum cover requirements, but not evidenced by layer 4.

<u>Site 2</u>

Site 2 is also problematic as regards structural performance and excessive maintenance and remedial work. This is typified by the large deflections seen, typically in excess of 7mm. The road was built 950mm in thickness over a vlei area by placing a rock base (layer 3) followed by the construction layers 2 and 1. The pavement was modelled to a depth of 2800mm including the in-situ layer 4 material. Below this depth no deflections were observed.

The DCP analysis classifies the profile as averagely balanced inverted with strength increasing from layers 1 to 3 and decreasing again in the lowest layer. Layer 3 corresponds to the rock layer and the MDD results, although yielding a modulus value may be regarded as unreliable in this layer.

The mechanistic analysis reveals very high vertical compressive strains in layer 2, exceeding

8000 microstrain. Layer 3 exhibits low values typical of a rock layer whilst layer 4 maximum strains of 2700 microstrains. From the stress sensitivity graphs it is seen that layers 1 and 2 may be regarded as stress softening due to the inclusion of clay materials and this exacerbates the performance problems at this site.

If the CBR cover curve design criteria for the site are compared to the results of the mechanistic analysis it is seen that under-design is apparent. This is due in part to the very different CBR profile to that of the MDD generated effective elastic moduli profile. This aspect will be discussed in more detail later. The inclusion of a rock layer at depth does not appear to improve performance of the road as predicted by the CBR design criteria.

Site 3

The road at site 3 is an old section of haul road constructed early in the life of the mine by contractors. It comprises material common to other sites but also a lime stabilised layer from 220mm to 460mm. Total structural thickness is 1000mm with in-situ material extending to a depth of 3400mm below which no deflections were observed. The structural performance of the road is excellent as evidenced in Figure 5.7, the small deflection measured being due in most part to the resilience of the stabilised layer. If the performance of the remaining layers are assessed without the stabilised layer, it is likely the lower layers in the road would not perform as adequately.

The DCP generated profile records it as a poorly balanced shallow structure, due to the effect of the lime stabilised layer. However, the mechanistically derived performance data tend to correspond well with the field observations of performance

The wearing course layer has a FOS of under 2 although there was no field evidence to support this result. The vertical strains recorded in layers 3 and 4 were particularly low, due primarily to the action of the stabilised layer. Referring to the stress sensitivity plots it may be seen that there is no clear evidence to support either stress softening or hardening from the data analysed.

When comparing the CBR cover curve design criteria with the results of the mechanistic analysis it is seen that despite the poorly balanced shallow profile, the road performs well and is not susceptible to the effects of high axle loads in the upper layers, primarily due to the load carrying capacity of the stabilised layer. This result is considered to have important implications in terms of the optimal structural design of a haul road.

5.5.2 Results of Mechanistic Analysis - Kromdraai Colliery

Results are presented in Appendix D2 for all Kromdraai Colliery site mechanistic analyses.

<u>Site 1</u>

The pavement at this site was constructed by contractors to design specifications. Pavement depth is the shallowest of the three sites considered; three layers extending down to 1000mm and the in-situ material modelled to a total depth of 2100mm below which no load induced deflections were seen. The road structural performance is good as reflected in Figure 5.7, with maximum deflections of approximately 2,5mm recorded. Mine personnel do not report any specific under performance of the road at this site.

The DCP generated profile for the site is that of a well balanced shallow structure with CBR values ranging from 211% in the top layer, decreasing to 17% in the in-situ material. The mechanistic analysis in terms of vertical strain reveals maximum values of approximately 1 000 microstrain in layers 2 and 4 whilst layer 3 exhibits a maximum of 2 500 microstrains. From the stress sensitivity plots no evidence of stress sensitivity is seen in any of the pavement layers.

The CBR cover curve design criteria for site 1 anticipates less cover than that actually placed and would appear to provide a reasonable, slightly conservative, base for design in this case. The larger vertical strains in the top of layer 3 are seen to coincide with the approach of the actual cover curve to the predicted cover requirements in the vicinity of layer 3. Layer 4 departs from the predicted curve and vertical strains are seen to reduce.

Site 2

The pavement was constructed by the mine and localised problems are experienced with deformation due to clay within and underlying the pavement construction. The structure consists of 3 structural layers to a depth of 1000mm placed on in-situ material (layer 4) which extends to a depth of 2750mm below which no deflections are observed. Construction in this area was not complete at the time of testing and an additional wearing course layer will be added to a total depth of approximately 200mm.

The road structural performance is adequate and a maximum deflection of 3,0mm recorded. Mine personnel report localised deformation as a result of clay in the construction and the classification (Figure 5.7) is accordingly lower than that suggested by the maximum deflection. The DCP generated profile is that of a well balanced shallow structure with corresponding CBR values from (a high) 354% in the top layer to 8% in layer 4.

The mechanistic analysis in terms of vertical strain reveals maximum values of approximately 1000 microstain in layer 2, 3000 in layer 3 and 1500 in layer 4. With reference to the stress sensitivity plots, layer 1 is omitted since an assumed effective elastic modulus was adopted for the layer in the absence of any MDD generated deflections at this depth. Layers 3 and (particularly) layer 4 exhibit stress softening tendencie., a fact which may be attributable to clay material in the pavement layers. Loads are carried in decreasing proportions as predicted by the DCP generated data.

The CBR cover curve design criteria for site 2 anticipates more cover required than is actually placed, especially in the vicinity of layers 3 and 4. The larger vertical strains seen in layer 3 appear to coincide with the CBR predicted localised under-design at this depth. The FOS values for layers 1 and 2 of approximately 12 and 6 correspond to the (assumed) load carrying capacity of each layer (due to the adopted of an assumed modulus for layer 1) and the reduced thickness of the top layer.

Site 3

The pavement at this site was constructed upon 4000mm of fill material by the mine. The construction was not complete at the time of testing and a wearing course layer of ±300mm was due to added. Three layers are identified, the top 2 layers extending to a depth of 650mm and the fill material (layer 3) modelled to a depth of 3300mm below which no deflections were observed. The road structural performance is classified as good with a maximum deflection of 2,4mm recorded. The DCP profile is that of an averagely balanced shallow structure, CBR values ranging from 269% in the top layer to 26% in the fill material.

The mechanistic analysis revealed maximum vertical compressive strains of 1300 and 1900 microstrains in layers 2 and 3 respectively. Some evidence of stress softening is seen in layers 2 and 3 due most probably to the presence of clay material in these layers. Again, the load carrying is fairly well predicted by the DCP generated balance curve.

The CBR cover curve design criteria for site 3 anticipates less cover than that actually constructed except in the vicinity of the top of layer 3 where the actual cover approaches predicted cover. The technique appears to give reasonable, if not slightly conservative results. Vertical strain at this point is approximately 1900 microstrains and seems to correspond well with localised cover reductions at this point. FOS values of 9 and 6 indicate that the applied stresses are much lower than the ultimate strength of the layers.

5.5.3 Results of Mechanistic Analysis - New Vaal Colliery

Results are presented in Appendix D3 for all New Vaal Colliery site mechanistic analyses.

Site 1

No meaningful data could be deduced from the recorded MDD deflections at this site due to inferred anchor movement during testing.

Site 2

The pavement at site 2 was constructed by the mine and consists of three layers to a depth of 1010mm. The road is located in a vlei area with soft material in-situ below the road.

Mine personnel report good/adequate performance over this section of road with only localised sections showing signs of distress. The classification reflects this and the associated maximum deflection of approximately 3,5mm. The DCP generated profile classifies the road as an averagely balanced deep structure, primarily due to the presence of a particularly weak layer 2.

The results of the mechanistic analysis show that in terms of vertical compressive strain at the top of layers 2 and 3, maximum values of 1800 and 1000 microstrain (respectively) are recorded. From the stress sensitivity plots, layers 1 and 2 are seen to be stress hardening, their strength increasing with increased trafficking.

The CBR cover curve design criteria again provide a conservative estimation of cover requirements. Whilst vertical strains in layers 2 and 3 are low, any reduction in cover thickness or layer strength may result in unacceptably high deflections in the pavement.

The FOS values calculated for layers 1 and 2 of approximately 6 and 9 (respectively) correlate with applied stresses in each layer but not with the DCP generated profile of increasing strength with depth.

<u>Site 3</u>

The pavement at site 3 was constructed by mine personnel and consists of three layers over a total thickness of 750mm. Road performance is adequate for the low level of traffic seen, but maximum deflections of 4,5mm and local deformation in wheel tracks result in some remedial work being required to maintain structural performance. The DCP generated profile is that of a poorly balanced deep structure, primarily due to the occurrence of a weak layer (CBR 30%) in the structure. This is borne out from the results of mechanistic modelling.

The mechanistic analysis reveals that this weak layer is subjected to maximum vertical strains of approximately 4500 microstrains and as such is the cause of much of the deformation seen in the road. This layer also exhibits stress softening which exacerbates the problem of excessive strains in the layer. In addition, the propensity of strain softening also explains the poor fit between MDD derived deflections and those obtained by mechanistic modelling. This may be alleviated by the addition of an extra (weaker) layer in the model.

5.6 Summary and Conclusions

The mechanistic analysis and quantification of existing pavement structural designs, incorporating a categorisation of structural performance and the assessment of damage criteria applied in the design of flexible roads and airfields revealed that the vertical compressive strain criterion is an important design parameter linking rut initiation in lower pavement layers with surface deformation. Table 5.2 summarises the results of the mechanistic analysis and quantification for mine haul roads from which it seen that the vertical compressive strain criterion correlates well with observed performance and maximum surface deflection.

When analysing the proposed FOS design criterion, it was found that since the applied stresses were much lower than the ultimate strength of the pavement layer materials and, since the FOS is dependant on the particular depth chosen in the analysis, the combination of high wheel loads and stress reversal in softer materials implies that the FOS criterion was not applicable to haul road design.

Regarding the propensity of the various pavement layers to stress-stiffen or -soften, some localised evidence of stress stiffening and softening was seen. This is however, more a function of the specific construction material used at each site rather than a universal phenomenon. Irrespective of the extent of over- or under-design apparent at each site, the analysis of deflection profiles generated from the MDD installations revealed that no induced vertical strains were seen in the pavement below a depth of approximately 3000mm.

By using the vertical compressive strain criterion in conjunction with the qualitative performance classification and maximum recorded surface deflection, an insight was afforded into the utility of the CBR- and DCP-based structural design techniques. The balance profile approach has limited application in the design of mine haul roads since one

Table 5.2 Summary of Structural Analysis - Mechanistic Evaluation Results

MINE	SITE	TOTAL LAYER	PERFORMANCE CLASSIFICATION			MECHANISTIC EVALUATION			
			Structural defect description	Perf. index. (1=poor)	Max deflection (mm)	Layer	Max vertical μstrain	FOS layer 1	FOS layer 2
Kriel	1	4	Deformation and rutting on a large scale	1	8,7	2	1950	5,0	2,9
						3	5450		
						4	4300		
	2	4	Deformation and rutting	2.5	6,4	2	8400	3,1	5,2
						3	Rock layer		
						4	2750		
	3	4	Excellent structural performance	8	1,6	2	Stabilised	1,7	No data
						3	1350		
						4	900		
Krom-draai	1	4	Localised deformation and rutting	6	2,5	2	950	9,0	4,3
						3	2600		
						4	1200		
	2	4	Localised excessive rutting	4	2,9	2	1350	11,9	6,3
						3	3000		
						4	1500		
	3	3	Localised deformation and rutting	6	2,3	2	1400	9,1	6,1
						3	1900		
New Vaal	1	4	Excellent structural performance	9	No data	No data	No data	No data	No data
	2	3	Localised deformation and rutting	6	3,4	2	1800	6,3	8,7
						3	1050		
	3	3	Localised excessive rutting	4	4,6	2	4650	6,3	8,5
						3	950		

of the most efficient and structurally sound designs incorporates a rock layer at a shallow depth, resulting in a poorly balanced shallow strength profile. An evaluation of the vertical strains generated within the pavement due to the applied load indicates that the strength balances to be avoided are those of inverted structures and, to a lesser extent, poorly balanced deep. Both are associated with excessive vertical strains in the pavement and poor structural performance.

With regard to the CBR cover curve empirical design approach, excessive vertical strains were generally associated with under-design of the pavement where less cover was placed than that predicted by the cover-curve method. The deficiencies inherent in the method, together with the potential for under-design associated with multi-layer structures limit the utility of the method when applied to mine haul road structural design.

CHAPTER 6

DERIVATION OF MECHANISTIC STRUCTURAL DESIGN CRITERIA

6.1 Introduction

This chapter addresses the derivation of the design criteria for the mechanistic design of surface mine haul roads. The structural performance categorisation introduced previously is used as a guide to the efficacy of the various existing haul road designs. Stresses and strains generated from the multi-layer elastic solution for the particular road test section are then compared with the structural performance categorisation to established suitable design criteria.

Construction material elastic moduli are assessed in terms of both the TRH14 classification and the DCP derived empirical relationship whereby suitable moduli for the various classes of granular materials used in haul road construction are derived. The catologue of modulus values facilitates the adoption of the technique without the need for separate tests to determine suitable modulus values, unless construction materials differ significantly from those analysed. An optimum structural design is then sought through consideration of the response of each pavement layer to the applied loads and the limiting design criteria previously assessed.

6.2 Derivation of Limiting Design Criteria

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 compressive strain for each layer below the top layer. As discussed in Chapter 5, the FOS does not appear to correlate with the structural performance classification. Mine test site roads exhibiting good structural performance do not necessarily exhibit correspondingly high layer FOS values, the latter being a function of the ultimate strength of each layer, which is normally not mobilised, the depth of the wearing course layer an the choice of depth at which the FOS is calculated. It is thus concluded that the FOS design criteria in the upper layers is not applicable to haul road design. Other design criteria may be more appropriate, particularly the vertical strain criterion. In the absence of any definitive criterion for the wearing course, a 200mm layer of compacted (95-98% Mod. AASHTO) good quality wearing course gravel would appear most appropriate, based on those mine sites wearing course layers exhibiting adequate structural performance.

Figure 6.1 relates the vertical compressive strain measurements taken at each mine site; those mine sites exhibiting poor performance and an associated excessive deformation/maximum deflection were seen to be associated with large vertical compressive strain values in one or more layers. When the maximum vertical strain is analysed in conjunction with the structural performance of the road (based on the product of performance index and daily traffic repetitions) as can be seen in Figure 6.2, as the structural performance index of the road is increased at a particular level of traffic volume, the maximum recorded strains in the pavement layers then decrease. Similarly, for a given performance index, increasing traffic volumes can be associated with lower maximum strain (and thus deformation) values. By plotting a maximum strain envelope (for a minimum satisfactory performance index of 7), the maximum allowable strain recommended for various traffic volumes and required performance levels is given by Equation [6.1];

$$\varepsilon_{max} = \exp^{(8{,}2 - 0{,}007.KT.I)} \qquad [6.1]$$

where ϵ_{max} = maximum allowable vertical compressive microstrain

KT = daily tonnage hauled on road (kt)

I = performance index (1-10)

Since the majority of mines' monthly tonnage lies in the region of 300kt, and using a performance index of 7 it is evident that an upper limit of 2000 microstrain should be placed on layer strain values in this case. A similar value is adopted for public road construction (Maree and Freeme, 1981) applicable to similar materials as are used in mine haul road construction, together with a strain reduction for increased standard axle repetitions and maximum allowable deformation. The Asphalt Institute (1973) design method for airport pavements subject to loads up to 1580kN recommend a maximum subgrade strain of between 2548-1422 microstrain for between 100 and $1x10^6$ repetitions. The 2000 microstrain limit

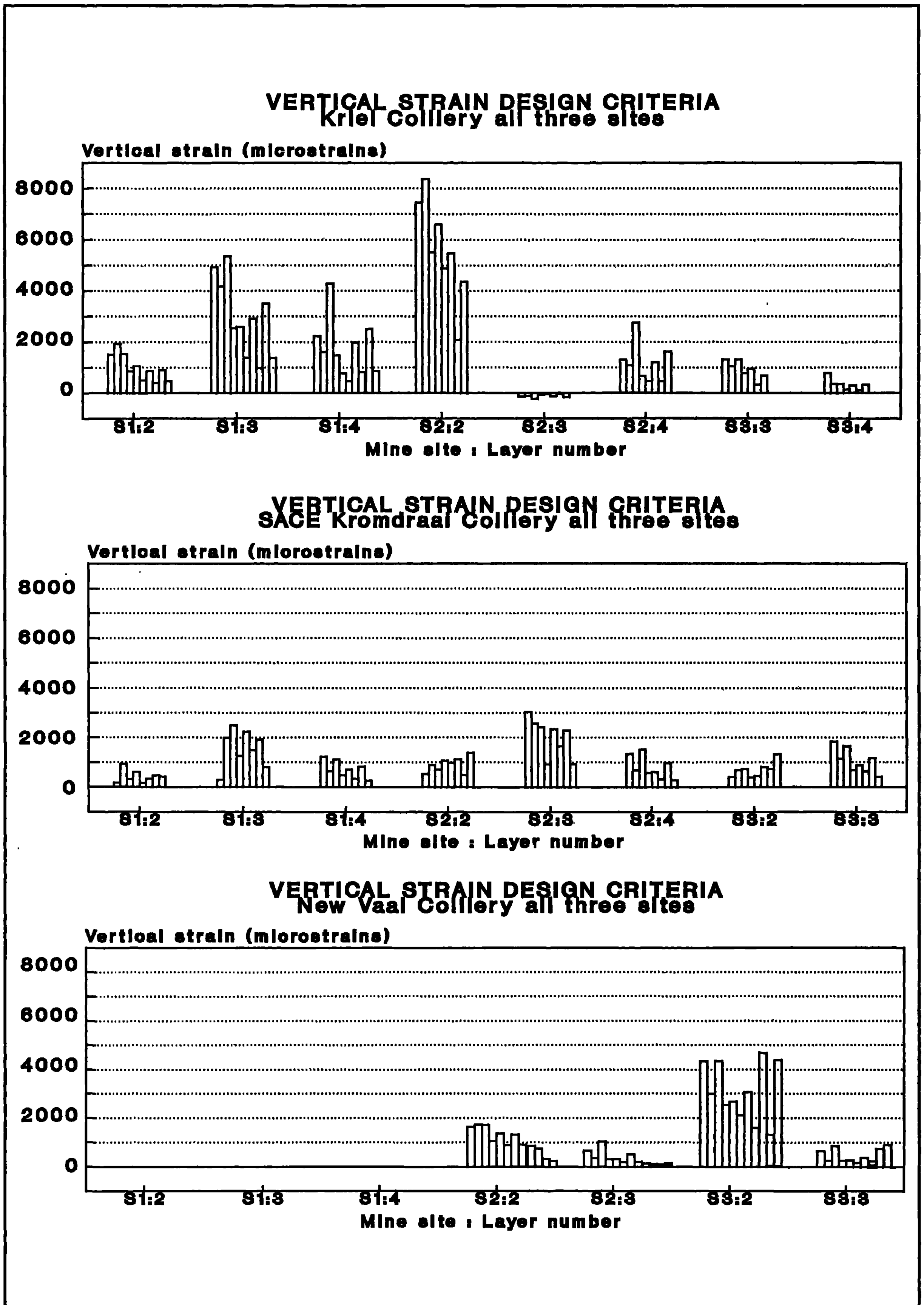


Figure 6.1 Vertical Strain Measurements at all Mine Sites

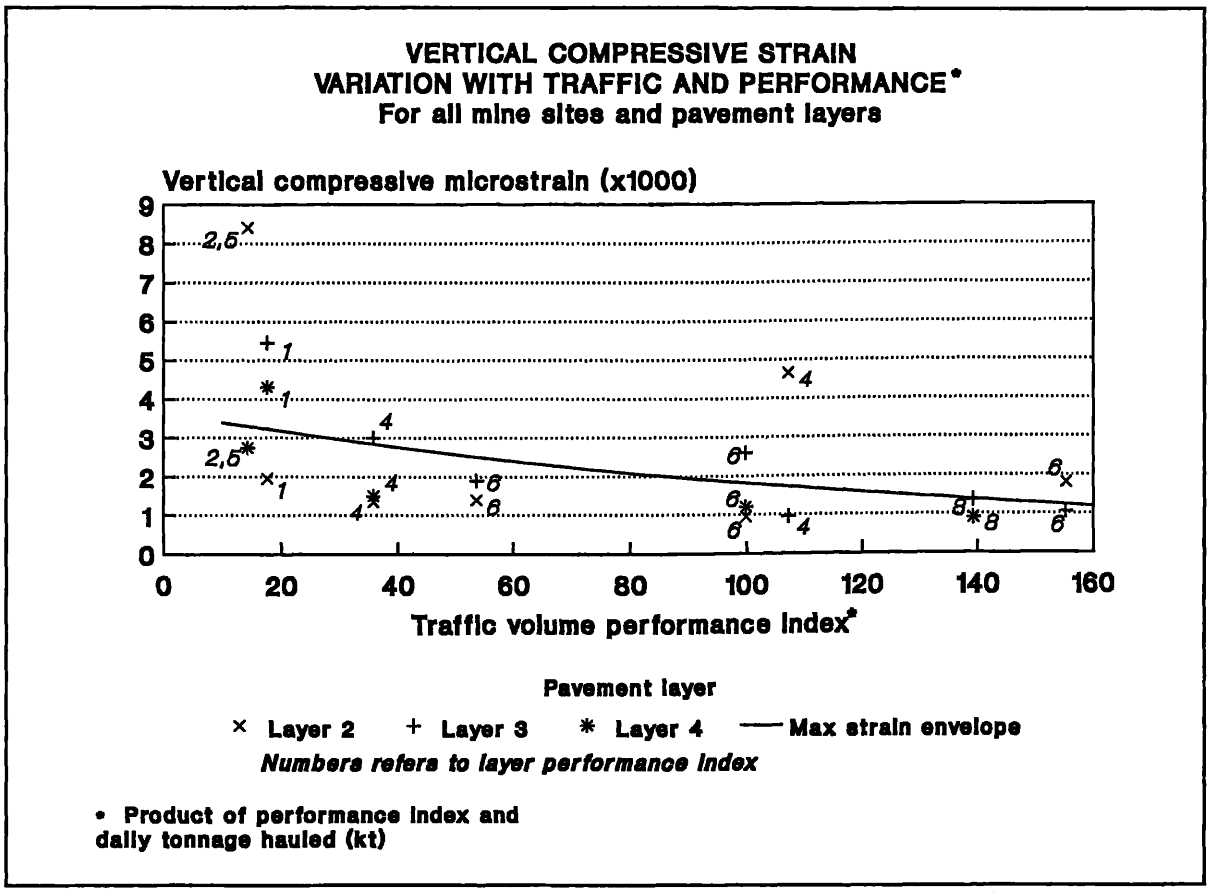


Figure 6.2 Maximum Vertical Compressive Strain Variation with Traffic and Structural Performance Index

is thus motivated as a design criteria for mine haul roads, based on typical traffic volumes and required performance index. Where traffic volumes are lower and/or poor structural performance is acceptable (short term roads) the maximum strain limit can be accordingly reduced following Equation [6.1].

6.3 Selection of Effective Elastic Modulus Values

The strains induced in a pavement are a function of the effective elastic modulus values ascribed to each layer in the structure. In order to facilitate mechanistic design of mine haul roads, some indication of applicable moduli values are required for the practical application of the method. This was achieved by considering the individual layer modulus values generated by the mechanistic analysis of existing pavements and comparing these values to established modulus values and the associated material classification.

For each test site analysed, each layer exhibited a range of effective elastic modulus values, dependant on the specific material used for road construction. Current data relating the range of moduli for granular materials, classified following CSRA TRH14 guidelines (Committee of State Road Authorities, 1985) is presented in Table 6.1. A classification for (amongst other materials) untreated gravel materials and dumprock is proposed in CSRA TRH 14. In all, six material groups are recognised, in descending order of strength and quality for roadbuilding purposes, from a G1-G3 (high quality graded crushed stone), G4-G6 (natural gravels), G7-G10 (gravel soil) to (DR) dumprock. Classification is based on material grading, Atterberg limits, CBR, swelling and field compaction characteristics. A summary of the applicable material characteristics for G1 to G10 and dumprock materials is presented in section 6.3 as they apply to haul road construction.

Tables 6.2-6.4 summarise the moduli values and associated classification for the materials used in each site pavement construction whilst Figure 6.3 presents the information graphically. As can be seen the modal material classification (ignoring in-situ material) is that of a G4-G6 gravel or low quality gravel where local mine ferricrete is used. The imported material used in the New Vaal construction does not differ significantly from this classification. It would therefore seem prudent to adopt blanket modulus values for these material types. A modulus range of 150-200MPa is proposed for G4-G6 gravels when used in wearing course and 75-100MPa for the same material when used in a base or sub-base layer. These values are slightly lower than the average values reported by SARB (1993), thereby accommodating local deviations from the standard material, compaction, stress softening effects, the presence of water and poor support from sub-grade materials. Values for the moduli of the in-situ sub-grade material are very much site and material specific and range from 17MPa to 388MPa and often exhibit stress softening. The use of DCP derived CBR values as outlined in section 4.2.4 may provide the most tractable approach in ascertaining suitable modulus values for this material. Data in Tables 6.1 and 6.5 may be used in conjunction with the CBR data to determine modulus values for these poorer quality (G7-G10) sub-grade materials.

The use of the DCP to investigate the structural performance of haul roads has been limited to the generation of balance profiles, CBR values for each layer and seed modulus for the

Table 6.1 Suggested Moduli Ranges (MPa) for Granular Materials (After Freeme, 1983 and updated by SARB, 1993)

CODE	MATERIAL DESCRIPTION	ABBREVIATED SPECIFICATION (CSRA, 1985)	OVER CEMENTED LAYER SLAB STATE	OVER GRANULAR LAYER OR EQUIVALENT	WET STATE (GOOD SUPPORT)	WET STATE (POOR SUP-PORT
G1	High quality crushed stone	86 - 88 % ARD impermeable	450 (250 - 1 000)	150	50 - 250	40 - 200
G2	Crushed stone	100 to 102 % Mod AASHTO	400 (200 - 800)	100 - 400	50 - 200	40 - 200
G3	Crushed stone	98 - 100 % Mod AASHTO	350 (200 - 800)	100 - 350	50 - 150	40 - 200
G4	Gravel base quality	CBR $\nless$ 80 PI $\ngtr$ 6	300 (100 - 600)	75 - 350	50 - 150	30 - 200
G5	Gravel	CBR $\nless$ 45 PI $\ngtr$ 10 - 15	250 (50 - 400)	40 - 300	30 -200	20 - 150
G6	Gravel low quality subbase	CBR $\nless$ 25	225 (50 - 200)	30 - 200	20- 150	20 - 150
Poisson's ratio 0,35						

Table 6.2 Layer Modulus and Classification for Kriel Colliery Sites

PAVEMENT LAYER MODULUS E_{eff} (MPa)												
	Site 1				Site 2				Site 3			
Layer	1	2	3	4	1	2	3	4	1	2	3	4
Average (MPa)	415	368	39	17	117	51	4175	29	421	2557	173	328
S Deviation σ (MPa)	110	98	9	2	60	15	801	10	156	150	49	109
TRH14 classification	G4	G4	G8	G8	G6	G7	Rock layer	G8	G4	Rock layer	G6	G5

Table 6.3 Layer Modulus and Classification for Kromdraai Colliery Sites

PAVEMENT LAYER MODULUS E_{eff} (MPa)												
	Site 1				Site 2				Site 3			
Layer	1	2	3	4	1	2	3	4	1	2	3	4
Average (MPa)	247	1113	49	99		337	116	129	55	517	144	
S Deviation σ (MPa)	88	354	19	31		47	44	31	3	154	28	
TRH14 classification	G5	?	G8	G6	No data	G4	G6	G6	G7	G4	G6	

Table 6.4 Layer Modulus and Classification for New Vaal Colliery Sites

PAVEMENT LAYER MODULUS E_{eff} (MPa)												
	Site 1				Site 2				Site 3			
Layer	1	2	3	4	1	2	3	4	1	2	3	4
Average (MPa)					197	32	73		144	32	168	
S Deviation σ (MPa)					51	16	26		29	7	54	
TRH14 classification					G6	G8	G7		G6	G7	G6	

Table 6.5 Suggested Modulus of Sub-grade Materials (after SARB, 1993)

CODE	SOAKED	MATERIAL	EFFECTIVE E-MODULUS (MPa)	
	CBR		WET STATE	DRY STATE
G7	$\nless$ 15	Gravel-soil	20 - 120	30 - 200
G8	$\nless$ 10	Gravel-soil	20 - 90	30 - 180
G9	$\nless$ 7	Gravel-soil	20 - 70	30 - 140
G10	$\nless$ 3	Gravel-soil	10 - 45	20 - 90

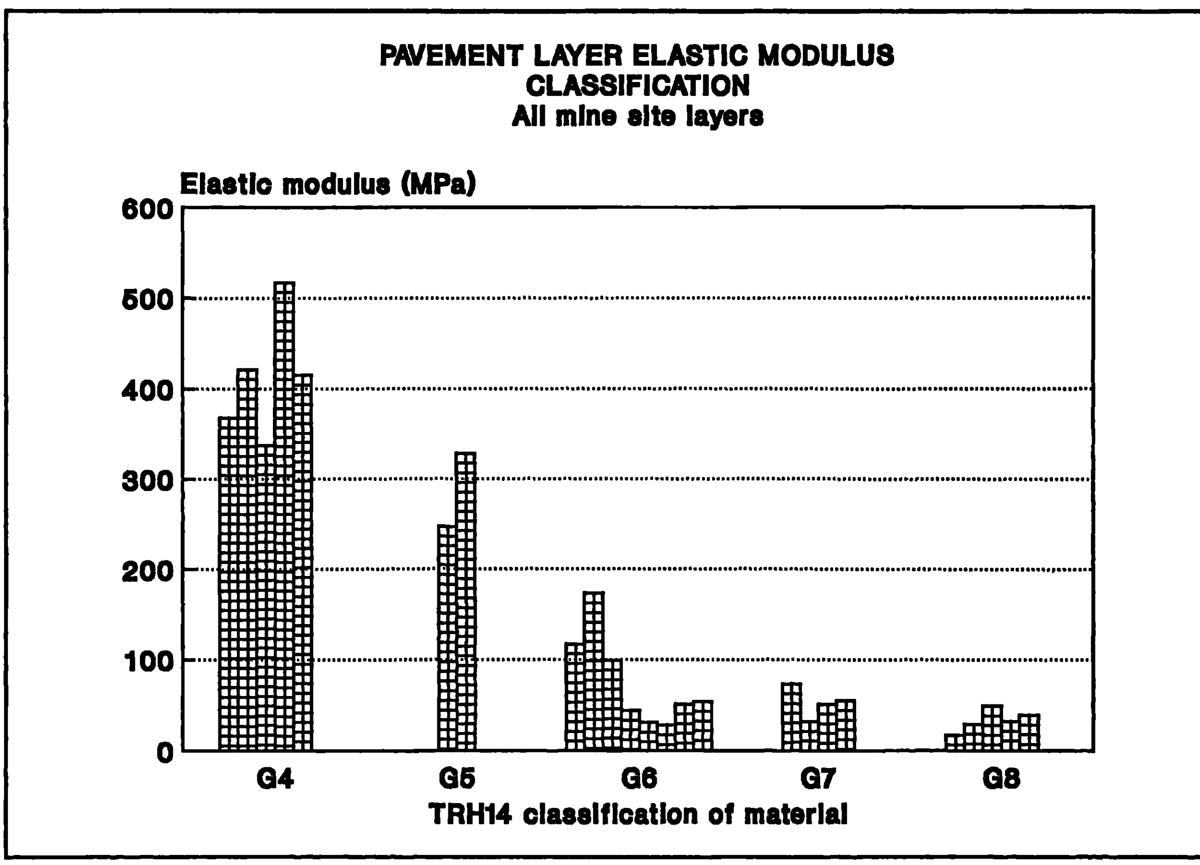


Figure 6.3 Range of Elastic Modulus Values Encountered for Various Material Classifications

multi layer elastic analysis. It has been shown in section 4.2.4 that the balance profile has limited application in the design of mine haul roads since one of the most efficient and structurally sound designs incorporates a rock layer at a shallow depth resulting in a poorly balanced shallow strength profile. In general terms the strength balances to be avoided are those of inverted structures and, to a lesser extent, poorly balanced deep. Both are associated with excessive vertical strains in the pavement.

The empirical relationship used to determine the seed modulus for the mechanistic model [Equation 5.2] has been reanalysed in the light of the final solutions for the layer modulus and the DCP penetration rate values (DN) as shown in Figure 6.4. Some trend is evident but the confidence limits calculated for the relationship are large and a solution within 80% confidence extends over two decades. The empirical relationship derived in this study for a 430kN wheel load and 630kPa contact stress is given in Equation [6.2].

$$\log(E_{eff}) = 2{,}281 - 0{,}3138(\log(DN)) \qquad [6.2]$$

The associated standard error of estimate is 0,487 and R^2=68%. Data pertaining to the analysis is given in Appendix D4.

It is difficult to motivate for the existence of a direct relationship between effective elastic modulus and DCP penetration rate due to the very different testing techniques employed to derive different characteristic parameters for the same material (shear failure for DCP and elastic response for MDD). This is evident when the effective elastic modulus is plotted against the pavement layer CBR value derived from the DCP testwork, as shown in Figure 6.5. Thus the relationship proposed above should be used with caution, bearing in mind the limitations associated with its derivation.

6.4 Summary of Recommended Mechanistic Design Procedure

The optimal mechanistic structural design of a surface mine haul road embodies the selection of target effective elastic modulus values for the construction materials available and the

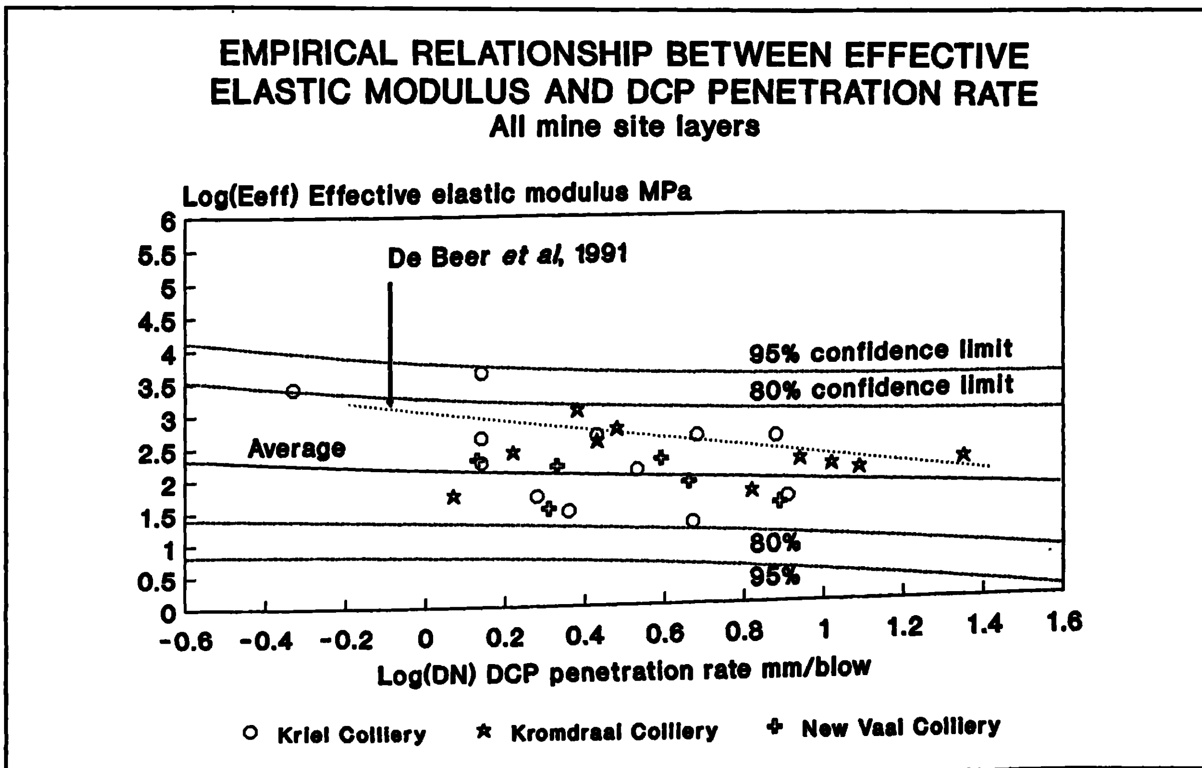


Figure 6.4 Empirical Relationship Between Effective Elastic Modulus and DCP Penetration Rate for Various Ultra-heavy Axle Loads.

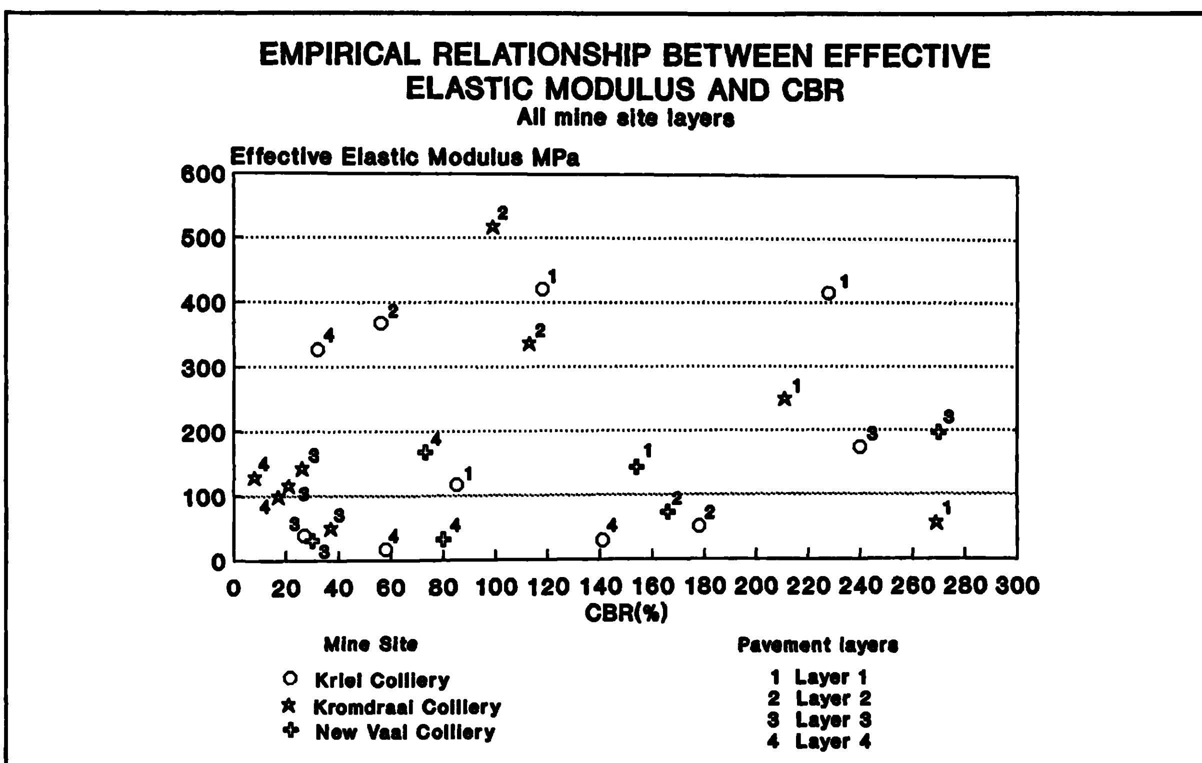


Figure 6.5 Relationship Between Effective Elastic Modulus and CBR for Various Ultra-heavy Axle Loads.

placement of those materials such as to optimise their performance both as individual layers and over the entire structure. Performance has been 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. In addition, of the various design options analysed at each mine test site, the inclusion of a rock layer immediately below the wearing course proffered the structure increased resilience to the applied loads without recourse to excessive structural thickness. These findings are examined as they appertain to the mechanistic structural design of mine haul roads.

Materials available on site for the construction of roads is derived from borrow pits or the pit itself. Borrow pit material comprises generally ferricrete and may be classified (following TRH14) as G4-G6. Material derived from in-pit working, typically sandstone parting, is classified as dumprock (DR). Selection criteria for these materials are analysed in terms of material grading, Atterberg limits, CBR, swelling and field compaction characteristics as a precursor to assigning target effective elastic modulus values to the material.

All natural materials will display a degree of inherent variability and a certain percentage of the population will exhibit poorer quality levels than those specified. TRH14 recommends that not more than 10% of the materials should have a quality level below the specification limit. These guidelines can be accepted for typical borrow pit material used in haul road construction, although poor quality materials may exceed the 10% limit. This deviation is accomodated by adopting the lower-bound modulus values reported in the Tables 6.1 & 6.5.

Grading

Construction materials classified following TRH14 should comply with the grading requirements given in Table 6.6. Recommendations regarding the design of roads with these materials (Freeme, 1983) limit G4-G5 to the road base and G6-G7 to the sub-base. However, the mechanistic analysis of road performance indicates that a G4-G5 gravel is suitable for base and sub-base layers in haul road construction. CSRA draft TRH20 (The Structural Design, Construction and Maintenance of Unpaved Roads), (Committee of State Road Authorities, 1990) guidelines in regard to recommendations for material selection in haul road construction are illustrated in Figure 6.4 in terms of the grading coefficient. This value should range between 16 and 34. In addition, a maximum material size of 75-100mm is recommended together with oversize index (percent retained on 37,5mm sieve) of $\leq 10\%$. The assessment of haul road functionality will provide confirmation of these recommendations as regards the specific requirements of mine haul road users. The remaining selection parameters are discussed in the following subsections.

Atterberg Limits

The Atterberg limits given in Table 6.7 apply to the soil fines ($<$0,425mm) of natural gravels (G4 and G5). In general, high plasticity material should be avoided due to the associated stress softening effect as discussed in Chapter 5.3. TRH20 recommendations are summarised in Figure 6.6 in which a shrinkage product value of between 100-365 (maximum preferably $<$240) is used. This value incorporates both the quantity of fines and the linear shrinkage of the material, similar approximate values derived from TRH14 recommendations for G4 and G5 materials are 90 and 150 respectively.

Bearing Strength and Swell

Bearing strength (7 day soaked CBR) and swell properties for typical construction materials are given in Table 6.8. TRH20 recommendations are limited to a bearing strength of CBR$\geq$15 at $\geq$95% Mod AASHTO compaction after 4 days soaking, approximately equivalent to a G6-G7 material.

Field Compaction

In order to achieve the target effective elastic modulus values for the various categories of materials available for construction, filed compaction requirements should also be considered. These are given in Table 6.9, according to the pavement layer position of the particular material. In all cases the moisture content of the various materials employed should be the optimum for the compaction plant employed to ensure that during compaction, instability or excessive movement of the material is avoided.

Table 6.6 Grading Requirements for Haul Road Construction Materials (after CSRA TRH14, 1985).

MATERIAL	GRADING REQUIREMENTS	
G4	Sieve size (mm)	Percent passing by mass
	53,0 37,5 26,5 19,0 13,2 4,75 2,00 0,425 0,075	100 85-100 - 60-90 - 30-65 20-50 10-30 5-15
G5 and G6	Should have a maximum size of 63mm or two-thirds of the compacted layer thickness, whichever is the smaller. A minimum grading modulus* of 1,5 (G5) and 1,2 (G6) should be obtained.	
G7	Should have a maximum size, in place, after compaction, not greater than two-thirds of the compacted thickness of the layer. A minimum grading modulus* of 0,75 should be obtained.	
DR (Dumprock)	Should have a maximum size not more than two-thirds of the compacted thickness of the layer and this should not exceed 300mm per lift.	

* Grading Modulus is given by;

$$GM = \frac{P_{2,00mm} + P_{0,425mm} + P_{0,075mm}}{100}$$

where $P_{2,00}$, etc., denotes the percentage retained on the indicated sieve size.

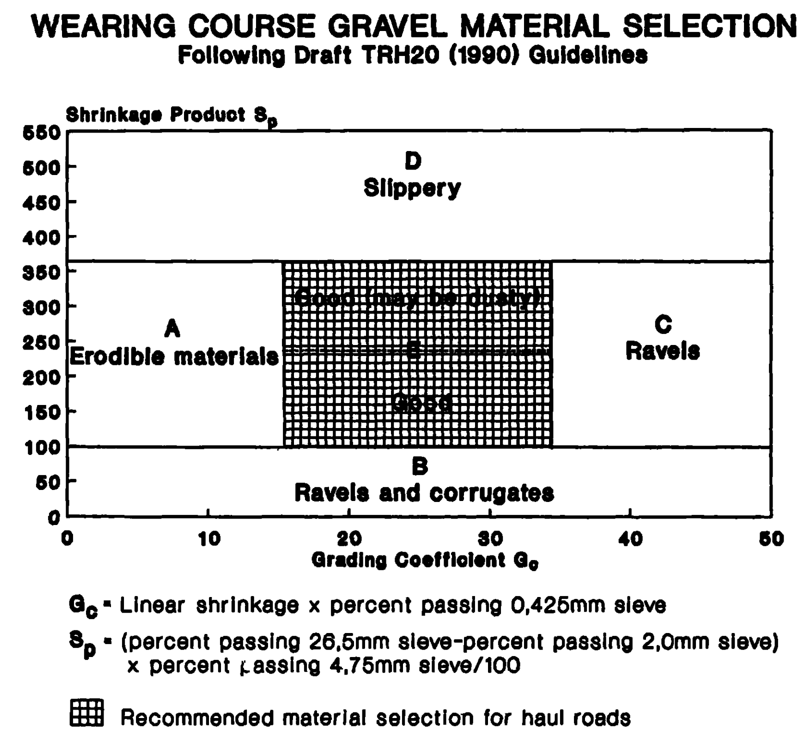


Figure 6.6 Relationship Between Shrinkage Product, Grading Coefficient and Performance of Haul Road Wearing Course Gravels (after CSRA, draft TRH20, 1990).

Table 6.7 Atterberg Limits for Haul Road Construction Materials (after CSRA TRH14, 1985).

MATERIAL	ATTERBERG LIMITS	
G3 and G4	Property	Value
	Liquid limit (max) Plasticity Index (max) Linear shrinkage (max) %	25 6 3
G5	Liquid limit (max) Plasticity Index (max) Linear shrinkage (max) %	30 10 5
G6 and G7	Plasticity Index (PI) should not exceed 12, or where a large course fraction is present, Plasticity Index is given by; $PI = 3.GM + 10$ Where Gm = Grading Modulus	

Table 6.8 CBR and Swell Properties for Haul Road Construction Materials (after CSRA TRH14, 1985).

MATERIAL	CBR AND SWELL PROPERTIES		
G3 and G4	Should have a CBR after soaking of not less than 80% at 98% Mod. AASHTO and a maximum swell of 0,2% at 100% Mod. AASHTO density		
G5	Should have a CBR after soaking of not less than 45% at 95% Mod. AASHTO and a maximum swell of 0,5% at 100% Mod. AASHTO density		
G6 and G7	PROPERTY	VALUE G6	VALUE G7
	Minimum CBR at 93 % Mod. AASHTO density.	25	15
	Maximum swell at 100 % Mod. AASHTO density	1,0	1,5

Table 6.9 Field Compaction Requirements for Haul Road Construction Materials (after CSRA TRH14, 1985).

PAVEMENT LAYER	CONSTRUCTION MATERIAL	RELATIVE COMPACTION
Base (upper and lower)	Natural gravel or gravel-soils (selected ferricrete) G4-G5 Dumprock (DR)	98% Mod. AASHTO Compaction is continued until movement under the roller is negligible
Subbase (upper and lower)	Natural gravel or gravel-soils (selected ferricrete) G5-G6	95% Mod. AASHTO
Selected layers	Natural gravel or gravel-soils (selected ferricrete) G5-G7	93% Mod. AASHTO

The strength of the in-situ material is also a critical factor in the structural design of a road. Values for the moduli of the in-situ sub-grade material are very much site and material specific and range from CBR 8% to 141%. The target effective elastic modulus for each of the material classifications considered above are given in Tables 6.1 and 6.5. A modulus range of 150-200MPa is 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. These values are slightly lower than the average values reported by SARB (1993), thereby accommodating local deviations from the specified standards and poor support from sub-grade materials. For in-situ materials, a range of effective elastic modulus values from 17MPa to 388MPa were encountered, often exhibiting stress softening. Modulus values recommended for this material over a range of CBR values are given in Table 6.10. TRH20 recommends the in-situ material be ripped and mixed, water being added to achieve optimum moisture content if necessary. The material should then be compacted to 90% Mod AASHTO. Dump rock material, consisting of selected sandstone or parting is assigned a target effective elastic modulus value of 3000 MPa which is derived from consideration of a G2-G10 stabilised gravel layer in an uncracked state as reported by SARB (1993). Since relatively large rock material is specified in the rock layer (< 300mm or ⅔ of the specified layer thickness), although not stabilised the layer is nevertheless likely to exhibit high strength and stiffness.

Table 6.10 Effective Elastic Modulus Values for In-situ Materials.

CBR(%) OF IN-SITU MATERIAL	**EFFECTIVE ELASTIC MODULUS* (MPa)**	
	Wet state	**Dry state**
CBR≥25	105	135
24≥CBR≥15	85	135
14≥CBR≥10	65	120
9≥CBR≥7	55	95
6≥CBR≥3	45	65
* Effective elastic modulus values derived from Equation 6.2 and Table 6.5 (after SARB, 1993)		

Recommendations regarding the structural design of surface mine haul roads are centred on the inclusion of a 500mm thick dumprock layer within the structure. The design proposed is based upon the findings of the mechanistic analysis of the Kriel Colliery site 3 road which incorporates a stabilised layer. The road comprises material common to other sites at Kriel but also a lime stabilised layer from 220mm to 460mm. The structural performance of the road is excellent as evidenced in Figure 5.7, the small deflection measured being due in most part to the resilience of the stabilised layer. Stabilisation techniques are expensive and the layers themselves subject to cracking if not adequately designed, thus the most tractable option is to use mine dumprock or parting material in place of the stabilised layer. The optimal location of this layer is immediately below the wearing course layer, thereby reducing deflections (and consequent deformation) in the lower layers to a minimum. Using this approach, a reduced structural thickness is realised without the attendant deformation and reduction in structural performance level that would otherwise be evident without a rock layer. The structural design, together with the associated minimum material specifications are depicted in Figure 6.7.

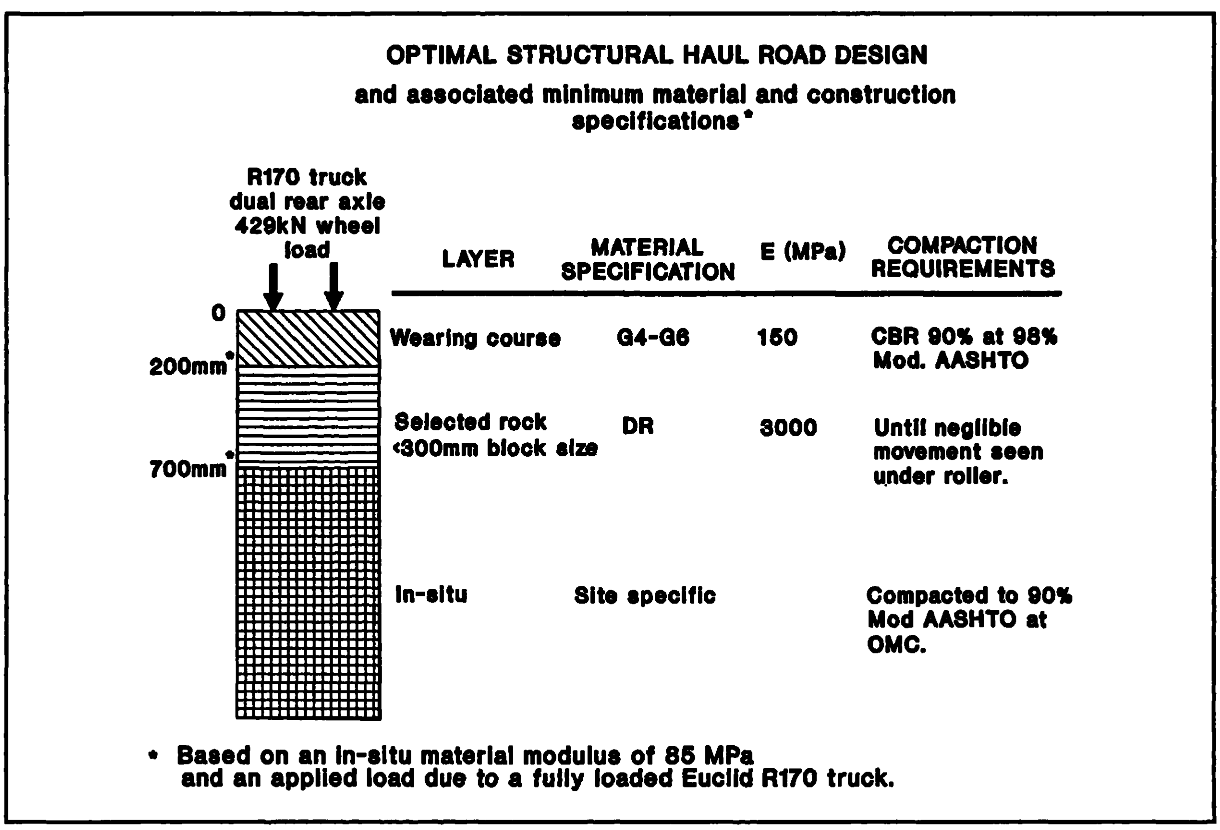


Figure 6.7 Optimal Structural Design Recommendations for Surface Mine Haul Roads.

The design criteria thus established together with the proposed target effective elastic modulus values for the various classes of materials locally available for haul road construction are applied to a typical structural design case study and the results discussed in the following Chapter.

CHAPTER 7

MECHANISTIC DESIGN OF A MINE HAUL ROAD - A CASE STUDY

7.1 Introduction

The design criteria derived from the mechanistic analysis of existing haul roads is used in this section to complete a comparative structural design for a road recently constructed at Kleinkopje Colliery. For comparative purposes, two design options are considered; the AMCOAL design based on the CBR cover curve design methodology, as constructed by site contractors and the mechanistically designed optimal equivalent as derived and discussed in Chapter 6. Finally, the cost implications of the optimal design are analysed.

7.2 Roadbuilding Materials

The road is constructed in the Block 2 area of the mine where mining has already taken place, the road foundation is thus spoil material that has been tipped and dozed, together with the replacement of a top soil layer. Roadbuilding materials available on the mine were assessed by contractors (Loma Lab, 1992). The entire mine area is underlain by sedimentary sandstones, shales and carbonaceous seams of the Vryheid Formation Ecca Group of the Karoó Sequence. Transported and residual soils overlie the site. Details of borrow pit materials are presented in Figure 7.1 and Table 7.1.

As can be seen from the data presented in Table 7.1 the available material has consistently low Plasticity Indices (<10), low linear shrinkage (<5,5%), well graded character and of high density (2131kg/m^3 at 8.2% moisture content). This gives rise to good CBR values of 37% at 90% Mod. AASHTO and 90% at 98% Mod. AASHTO. Classification following TRH14 is generally G4-G6. The TRH14 classification suggests suitability from the point of view of public road construction. In mine haul road construction this material will be used to construct all the layers of the road, albeit at various levels of Mod. AASHTO compaction.

For comparative purposes, two design options are considered; the AMCOAL design based

Table 7.1 Laboratory Classification Details of Borrow Pit Material

Test pit No.	Depth of layer (m)		Soil Description	Sieve Analysis						Liquid limit (%)	Plasticity index (%)	Linear shrinkage (%)	Grading modulus	CBR %					MOD AASHTO		TRH14	Suitability
	From	to		Percent passing										MOD AASHTO Density (%)				Swell at 90%	Density kg/m³	Moisture content (%)		
				37,5	13,2	4,75	2,00	0,425	0,075					90	93	95	98					
BPA1	0,4	1,8	Gravel: ferruginous concretions	100	98	81	58	44	30	27	11	5,5	1,68	19	33	48	77	0,1	2091	9,1	G6	Lower subbase
BPA2	0,3	1,9	Gravel: ferruginous concretions	100	100	88	67	50	34	30	11	5,5	1,49	12	33	46	73	0,1	2053	10,0	G6	Lower Subbase
BPA3	0,4	2,0	Gravel: ferruginous concretions	100	97	67	48	36	16	17	5	2,0	2,00	20	36	52	84	0,0	2139	8,2	G5/G6	Subbase/base
BPA4	0,3	2,3	Gravel: ferruginous concretions	100	90	64	48	40	24	24	10	4,5	1,88	17	36	57	97	0,1	2119	7,7	G5	Subbase
BPA5	0,3	2,3	Gravel: ferruginous concretions	100	93	68	53	42	17	18	4	2,0	1,88	25	48	70	120	0,0	2214	7,0	G5/G4	Subbase/base
BPA6	0,6	2,0	Gravel: ferruginous concretions	100	96	77	59	44	24	21	8	3,5	1,67	18	32	45	72	0,1	2147	8,0	G5	Subbase
BPA7	0,3	1,4	Gravel: ferruginous concretions	100	98	74	60	49	24	21	8	3,5	1,68	22	37	50	86	0,1	2112	8,3	G5	Subbase
BPA8	0,5	1,5	Gravel: ferruginous concretions	100	94	70	57	48	19	20	8	3,5	1,80	23	41	60	100	0,1	2104	7,9	G5	Subbase
BPA9	0,5	1,7	Gravel: ferruginous concretions	100	93	71	49	44	19	22	7	3,0	1,95	22	43	67	115	0,2	2133	8,6	G5	Subbase
BPA13	0,4	1,6	Gravel: ferruginous concretions	100	96	69	50	37	21	22	10	4,0	1,88	21	36	50	82	0,0	2204	7,1	G5	Subbase
BPA16	0,3	1,4	Gravel: ferruginous concretions	100	100	93	77	61	41	27	5	2,0	1,21	20	34	48	80	0,0	2124	7,9	G6/G5	LSB/subbase

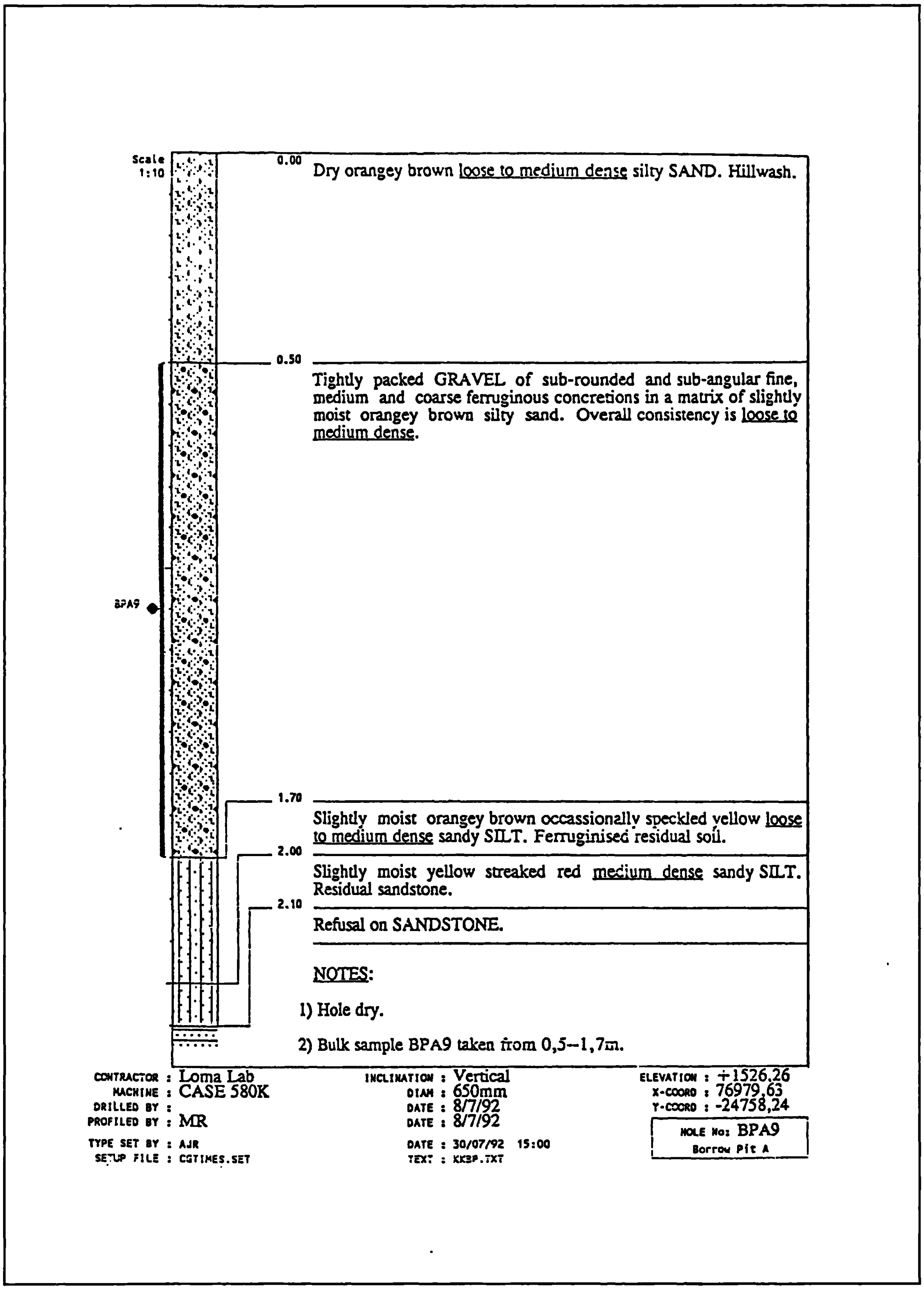


Figure 7.1 Soil Profile From Borrow Pit A, Kleinkopje Colliery (after Loma Lab, 1992)

on the CBR cover curve design methodology, as constructed by site contractors and the mechanistically designed equivalent. It is assumed that in-situ and road construction material properties remain the same irrespective of the structural design technique adopted. For both options a minimum wearing course thickness of 200mm, compacted to a density of 98% Mod. AASHTO is adopted as recommended in the previous chapter. An Euclid R170 truck is used to assess the response of the structure to applied loads generated by a fully laden rear dual axle (429kN per wheel, 630kPa contact stress) and the assumption is made of no load induced deflections below 3000mm. The various design options are summarised in Figure 7.2.

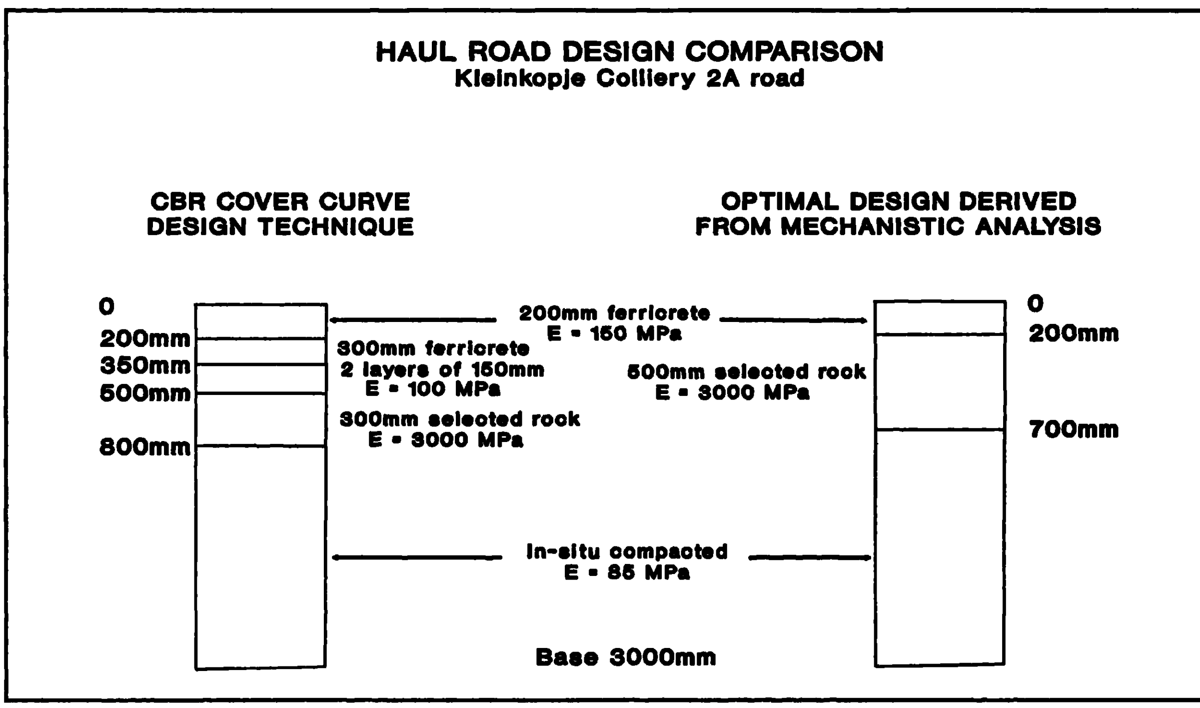


Figure 7.2 Haul Road Structural Design Options Investigated

7.3 CBR Cover Curve Design

The cover curve and layer strength diagram is given in Figure 7.3 for the Kleinkopje road, based on a compacted in-situ material CBR of 17% minimum. Structural design data is given in Table 7.2. The design was analysed mechanistically to determine the likely structural performance of the road in the light of those critical design factors previously

Table 7.2 CBR Structural Design Data

Layer	Layer Thickness (mm)	Mod. AASHTO compaction (%)	CBR achieved (%)	Assumed effective elastic modulus (MPa)*	Material description
1	200	98	90	150	Selected ferricrete G4/G5
2	150	95	50	100	Selected ferricrete G4/G5
3	150	93	35	100	Selected ferricrete G4/G5
4	300		>200	3 000	Selected sandstone, <300mm block size or < ⅔ layer thickness
5	In-situ		17	85	In situ compacted G7
* Values derived from Tables 6.1 and 6.10					

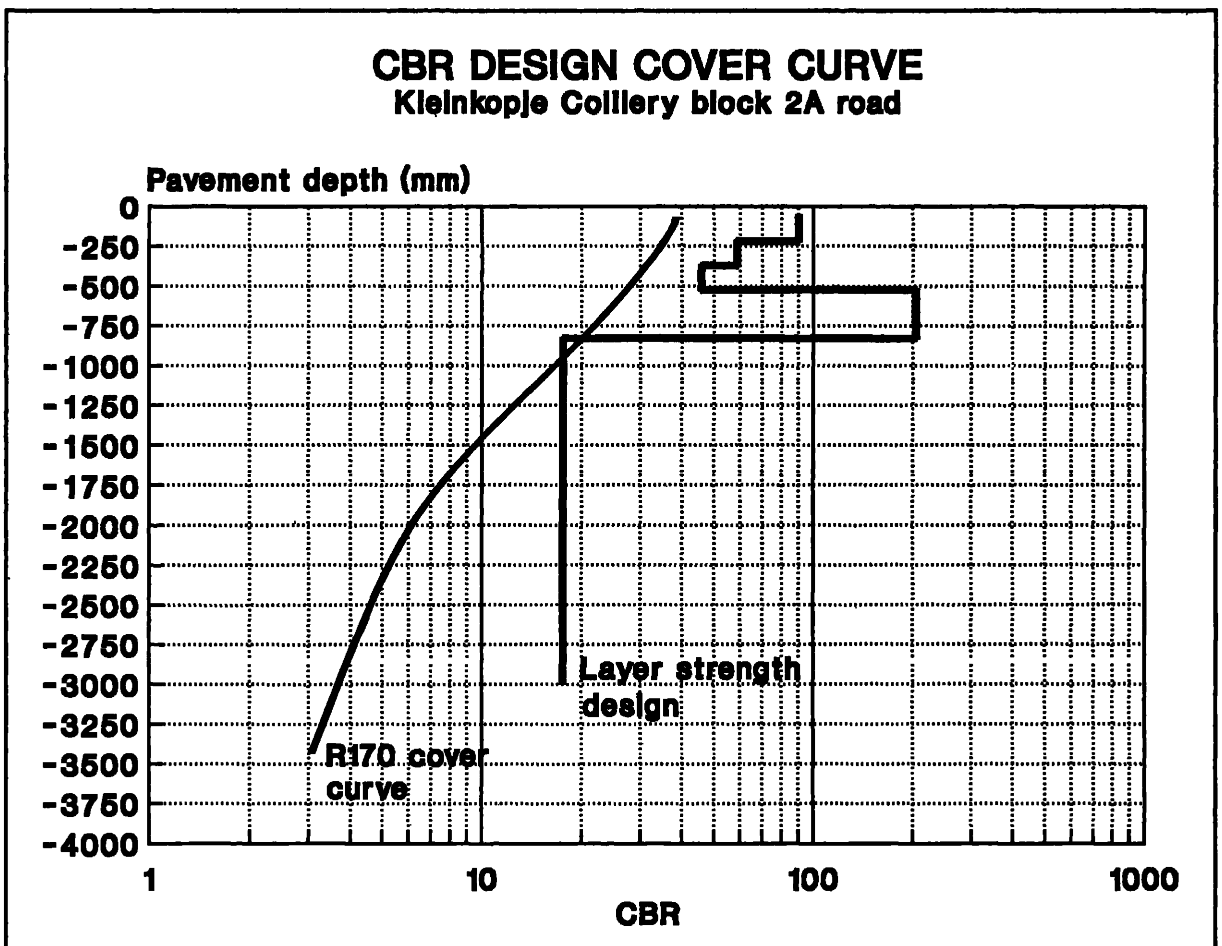


Figure 7.3 CBR Cover Curve For Kleinkopje Colliery Comparative Analysis

identified. In the case of Kleinkopje, a performance index of 7 was used in conjunction with 300kt monthly coal production which gave an upper limit to the load induced strains of approximately 2000 microstrain.

The data in Table 7.3 relates to the results of the mechanistic analysis of the CBR derived cover curve design. It is evident that excessive vertical compressive strains are generated in the top of layers 2 and 3. Strains in excess of 2000 microstrain are associated with an unacceptable amount of rutting and pavement deformation for this particular level of performance and traffic. Surface deflections generated by the applied load of 3,65mm do not appear excessive but when accompanied with the severe load induced strains, will eventually initiate structural failure. The comments made regarding the inapplicability and under-design apparent with the CBR design technique are borne out by these results, specifically the large vertical strains developed in the pavement as the design layer strengths approach the cover curve line. It is thus prudent to investigate design alternatives based on the results discussed in Chapter 6.

7.4 Optimal Haul Road Design

The design proposed is based upon the findings of the mechanistic analysis of existing haul roads. Of particular importance in this respect is the Kriel Colliery site 3 road which incorporates the stabilised layer. Whilst stabilisation techniques are expensive and the layers themselves subject to cracking if not adequately designed, the most tractable option is to use mine spoil rock material in place of the stabilised layer. The design adopted is depicted in Figure 7.2 and described in Table 7.4. The design is analysed mechanistically to determine the likely structural performance of the road in the light of the critical design factors previously identified.

The data in Table 7.5 relates to the results of the mechanistic analysis of the optimal design. It is evident that no excessive vertical compressive strains are generated in the structure, primarily due to the support generated by the shallow rock layer. Maximum vertical strains of 1505, 70 and 1078 microstrain are developed in layers 1, 2 and 3 respectively. Maximum

Table 7.3 Results of Mechanistic Analysis of Proposed CBR Based Design Technique

```
Kleinkopje CBR design assessment R170 rear full

        ELASTIC  POISSONS    LAYER
        MODULUS  RATIO       THICKNESS

1        150.    0.350     200.000 MM
2        100.    0.350     299.999 MM
3       2999.    0.350     299.999 MM
4         85.    0.350    2199.996 MM
5      29993.    0.350     SEMI-INFINITE

  TWO LOAD(S), EACH LOAD AS FOLLOWS              LOCATED AT
  TOTAL LOAD.....      428.96 KN           LOAD    X        Y
  LOAD STRESS....     629.86KPA             1    0.000    0.000
  LOAD RADIUS....      465.62 MM            2 1199.998    0.000

  X-Y POINT(S)                        RESULTS REQUESTED FOR SYSTEM LOCATION(S)
  X=            0.00    600.00        DEPTH(S)
  Y=            0.00      0.00        Z=  0.00 201.00 351.00 501.00 801.00


  0.00  LAYER NO  1
         DISPLACEMENTS
          UZ   0.3650E+01 0.2304E+01
         NORMAL STRAINS
          EZZ  0.1860E-02 0.1095E-03

  201.00  LAYER NO  2
         DISPLACEMENTS
          UZ   0.3115E+01 0.2348E+01
         NORMAL STRAINS
          EZZ  0.4593E-02 0.3983E-03

  351.00  LAYER NO  3
         DISPLACEMENTS
          UZ   0.2437E+01 0.2227E+01
         NORMAL STRAINS
          EZZ  0.4235E-02 0.1074E-02

  501.00  LAYER NO  4
         DISPLACEMENTS
          UZ   0.1907E+01 0.2054E+01
         NORMAL STRAINS
          EZZ  0.8003E-04 0.1464E-03

  801.00  LAYER NO  5
         DISPLACEMENTS
          UZ   0.1867E+01 0.2025E+01
         NORMAL STRAINS
          EZZ  0.1394E-02 0.1407E-02
```

surface deflections are approximately 2mm, reducing to 1,52mm in the in-situ material at a depth of 700mm. Deflections at a similar depth for the CBR based design in the in-situ material (800mm) are reduced to 1,43mm (compared with 2,02mm). The proposed optimal design thus provides a better structural response to the applied loads as does the thicker CBR based design and, in addition, does not exceed any of the proposed design criteria for the particular performance index and traffic volume used in the analysis. The mechanistically designed road can accommodate a 25% increase in traffic volumes before the critical limiting vertical compressive strain is exceeded. Overdesign in this manner accommodates deviations from the insitu material modulus of 85MPa.

Table 7.4 Optimal Structural Design Data

Layer	Layer Thickness (mm)	Mod. AASHTO compaction (%)	CBR achieved (%)	Assumed effective elastic modulus (MPa)*	Material description
1	200	98	90	150	Selected ferricrete G4/G5
2	500		>200	3 000	Selected sandstone, <300mm block size or <⅔ layer thickness
3	In-situ		17	85	In situ compacted G7
* Values derived from Tables 6.1 and 6.10					

7.5 Cost Implications of Optimal Design

A cost comparison was compiled based on contractor tender unit costs for the construction of the 2A road at Kleinkopje. Full details of the contractor unit and total costs for the construction of the road, based optimal (mechanistic) design approach, are given in Appendix E from data compiled by Purchase & Rowan (1993). This includes preliminary and general costs which are assumed not to vary with varying pavement structures and are thus not variables in this comparison context. It is also assumed that rock and borrow-pit material are within the free-haul distance of the construction site.

Table 7.5 Results of Mechanistic Analysis of Proposed Optimal Design

```
Kleinkopje optimal design assessment R170 rear full

        ELASTIC   POISSONS     LAYER
        MODULUS    RATIO      THICKNESS

  1       150.    0.350     200.000 MM
  2      2999.    0.350     499.999 MM
  3        85.    0.350    2299.995 MM
  4     29993.    0.350    SEMI-INFINITE

TWO   LOAD(S),EACH LOAD AS FOLLOWS              LOCATED AT
TOTAL LOAD.....     428.96 KN              LOAD    X        Y
LOAD STRESS....    629.86KPA                 1   0.000    0.000
LOAD RADIUS....     465.62 MM                2 1199.998   0.000

X-Y POINT(S)                          RESULTS REQUESTED FOR SYSTEM LOCATION(S)
X=     0.00    600.00                 DEPTH(S)
Y=     0.00      0.00                Z=   0.00 201.00 701.00

0.00  LAYER NO  1
      DISPLACEMENTS
       UZ  0.2072E+01 0.1555E+01
      NORMAL STRAINS
       EZZ  0.1505E-02 0.3127E-03


201.00  LAYER NO  2
      DISPLACEMENTS
       UZ  0.1579E+01 0.1644E+01
      NORMAL STRAINS
       EZZ  0.7030E-04 0.2137E-04

701.00  LAYER NO  3
      DISPLACEMENTS
       UZ  0.1520E+01 0.1620E+01
      NORMAL STRAINS
       EZZ  0.1078E-02 0.1077E-02
```

The variable costs taken into account are those of the volume and area of materials required and the associated costs of placing and compaction. Costs are analysed under two categories; preliminary and general costs and haul road construction costs. Preliminary and general costs are assumed to remain constant for the purposes of the analysis and amount to R410 000, or R164 000 per kilometre of road. Road drainage, berm construction and finishing are also assumed to remain constant irrespective of the design chosen.

Table 7.6 summarises the amounts and cost of the various activities as they apply to the CBR and optimal mechanistic-based designs. From an analysis of the construction costs for each design it is seen that a cost saving of R155 060, or 25% could be realised by adopting the

Table 7.6 Cost Comparison of Design Options (Excluding Preliminary and General Costs).

CBR-BASED DESIGN			OPTIMAL DESIGN		
ACTIVITY	**AMOUNT**	**COST (R)**	**ACTIVITY**	**AMOUNT**	**COST (R)**
Compaction of in-situ	$27000m^2$ $230m^3$	9 720 1 256			
Compaction and treatment of road-bed	4 $050m^3$ 6 $480m^3$	8 465 16 913	Compaction of in-situ	$10530m^3$	22 008
Place and compact rock fill layer	7 $300m^3$	39 858			
Place and compact rock layer	18 $750m^3$	102 375	Place and compact rock fill layer	8 $760m^3$	47 830
Place and compact sub-base layer	9 $375m^3$	108 468			
Place and compact base layer	9 $375m^3$	108 468			
			Place and compact rock base layer	31 $250m^3$	170 625
Place and compact wearing course	12 $500m^3$	144 625	Place and compact wearing course	12 $500m^3$	144 625
Finish, including drains and berms	$1000m^3$	8 670	Finish, including drains and berms	1 $000m^3$	8 670
	$7500m^3$	56 175		7 $500m^3$	56 175
	2,5km	7 650		2,5km	7 650
TOTAL		**612 643**			**457 583**

mechanistic-based optimal design, by virtue of the reduced material volumetric and compaction requirements. In terms of total construction cost (including preliminary and general costs), a 15% cost saving per kilometre is realised. In addition, further benefits should accrue in terms of reduced operating and maintenance costs arising from the superior structural performance of the road as evidenced from the foregoing analysis.

7.6 Summary

The design criteria derived from the mechanistic analysis of existing haul roads was used in this section to complete a comparative structural design costing exercise for a road recently constructed at Kleinkopje Colliery. Two design options were considered; the AMCOAL CBR cover curve design methodology and the mechanistically designed optimal equivalent, based on the design catalogue presented in Chapter 6 and the particular in-situ material strength and load characteristics prevalent in the 2A area at Kleinkopje.

It was assumed that in-situ and road construction material properties remain the same irrespective of the structural design technique adopted. For both options a minimum wearing course thickness of 200mm was used, compacted to 98% Mod AASHTO. The in-situ material was ascribed a CBR of 17 and a modulus of 85MPa. The CBR cover curve design incorporated 4 layers, including a rock-fill layer above the in-situ material. In contrast, the optimal mechanistic equivalent for this road consisted of 2 layers above insitu.

From an analysis of vertical compressive strains developed in each layer due to the applied load of a R170 truck, it was found that excessive strains were developed in layers 2 and 3 of the CBR-based design. The optimal design did not evidence any excessive strains, primarily due to the support generated from the shallow rock layer. The proposed optimal design thus provided a better structural response to the applied loads than did the thicker CBR based design and, in addition, did not exceed any of the proposed design criteria for the particular performance index and traffic volume used in the analysis.

A cost comparison of the two designs was compiled based on contractor tender unit costs for the construction of the 2A road at Kleinkopje. The variable costs taken into account were those of the volume and area of materials required and the associated costs of placing and compaction. By virtue of the reduced material volumetric and compaction requirements associated with the optimal design, a cost saving of R155 060, or 25% was realised. In terms of total construction cost (including preliminary and general costs), a 15% cost saving was realised over the CBR-based design.

The optimal mechanistic design derived in the analysis is based on the particular in-situ material strength, applied load and required road performance (at a particular traffic volume) characteristics. From Equation [6.1] it may be seen that if traffic volume from the 2A pit were to increase, the structural performance of road, based on the CBR design, would further deteriorate. However, even with a 25% increase in traffic volume, the strains generated in the various layers of the mechanistically designed pavement remain below the design criteria. When departures are made from the 85MPa in-situ material, Table 6.10 can be used to down-grade the applicable material modulus according to the particular CBR value of the material. If the type of truck changes, or the required performance index or tonnage hauled on the road, these can be modified in the analysis itself, following Equation [6.1]. In this respect the mechanistic design methodology and catalogue of values is transferable between sites.

CHAPTER 8
SUMMARY OF STRUCTURAL DESIGN RESEARCH

8.1 DCP Analysis of Pavements

Regarding the empirical analysis and quantification of existing pavement structural designs, the use of the Dynamic Cone Penetrometer in the context of haul road structural design investigations was employed to determine the location of various pavement layers, the California Bearing Ratio (CBR) values of these various layers and the overall balance of the structural design. The results generated in the first instance confirm the classification of test sites proposed in the experimental design for the site location matrix. In general, those sites showing a shallow structure, in which the majority of the pavement strength lies in the upper layers may be more sensitive to increased wheel loads and consequential failure of the upper layers. A deep structure, in contrast, would be less sensitive to any increase in wheel loads, but may well show signs of excessive permanent deformation in the weaker upper layers. The extent to which these effects are seen in haul roads can only be reliably determined from in-situ deflection measurements.

It has been shown that the balance profile approach has limited application in the design of mine haul roads since one of the most efficient and structurally sound designs incorporates a rock layer at a shallow depth resulting in a poorly balanced shallow strength profile. In addition, the pavement strength-balance concept focuses on the upper 1,8m of material, which, for most mine sites generally includes a portion of sub-grade. The strength-balance concept does not address whether the pavement as a whole is suited to the sub-grade strength. In general terms the strength balances to be avoided are those of inverted structures and, to a lesser extent, poorly balanced deep. Both are associated with excessive elastic vertical compressive strains in the pavement.

8.2 California Bearing Ratio (CBR) Design Procedure

Although the DCP data affords an insight into the actual road structure as opposed to the design structure and the strength of each layer actually achieved in the field, the extent to which each type of design fulfils the structural performance requirements can only be determined from analysis of the response of each layer to the applied loads. As a precursor to the analysis, the California Bearing Ratio design technique was investigated in which CBR data generated from the DCP investigation is compared to actual cover requirements predicted from the CBR design method. Although the CBR method is a simple and straight forward design method based on and improved by considerable practical experience, numerous disadvantages were found when applying the method to mine haul road design problems. Mine haul road structures consist of various layers of differing material each with its own specific elastic and other properties. More specifically, the CBR method was based on empirical results relating to the design of asphalt-surfaced airfield pavements for wheel-gear loads up to 4 400kN. When aggregate-surfaced mine haul roads are considered in conjunction with stabilised bases, albeit at similar load levels, the same approach is of questionable validity. The graphical relationship proposed by Ahlvin in conjunction with the modified CBR design technique would therefore also not appear to be applicable to haul road structural design. Simple extrapolation of these empirical design criteria to accommodate higher axle loads and different pavement layer materials can lead to serious errors of under- or over-design.

The deficiencies inherent in the development of the CBR design method militate against using the techniques for the structural design of mine haul roads. When the results of the DCP redefined layer strengths are analysed in conjunction with the CBR cover curves generated, it would appear that the method, when applied judiciously, can be used to determine safe (total) cover over in-situ materials, although the extent of over or under design associated with the method cannot be qualified. The method is thus exclusively recommended to design cases where no surface layers exist above standard gravel bases. Where cemented or stabilised layers are included in the design, or where the optimal structural design is sought, due to the very different properties of the layer in comparison to normal roadbuilding gravels, a mechanistic design techniques should be employed which can account for the different material properties and more accurately predict their performance.

8.3 Derivation of Mechanistic Structural Design

The derivation of the design criteria for the mechanistic design of surface mine haul roads was based on the structural performance categorisation of mine haul roads. Stresses and strains generated from the multi-layer elastic solution for the particular road test section were then compared with the structural performance and traffic volume categorisation to established suitable design criteria. Construction material elastic moduli were assessed in terms of both the TRH14 and TRH20 classification and the DCP derived empirical relationship whereby suitable moduli for the various classes of granular materials used in haul road construction were derived.

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 compressive strain for each layer below the top layer. It was found that the vertical strain criterion correlates well with structural performance/traffic volume of the road; those mine sites exhibiting poor performance and an associated excessive deformation/maximum deflection were seen to be associated with large vertical compressive strain values in one or more layers. From analysis of the data it was found that when using a performance index of 7 and 300kt coal production per month, an upper limit of 2000 microstrain should be placed on layer strain values. Strain values exceeding this value have been shown to be associated with unacceptable structural performance in both public road and airfield design. 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 is concluded that this criteria is not applicable to haul road design since the applied stresses were much lower than the ultimate strength of pavement layer material, which was normally not mobilised. In addition, the location of the point in the wearing course layer at which the FOS is calculated is very much dependant on layer thickness, stress reversals being seen in relatively thin, poorly supported layers. In the absence of any definitive criterion, a 200mm layer of compacted (95-98% Mod. AASHTO) good quality gravel is recommended. This recommendation is derived from the observation of mine site wearing course layers which exhibited adequate structural performance.

The optimal mechanistic structural design of a surface mine haul road embodies the selection 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. Performance has been 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. In addition, of the various design options analysed at each mine test site, the inclusion of a rock layer immediately below the wearing course proffered the structure increased resilience to the applied loads without recourse to excessive structural thickness.

8.4 Selection of Effective Elastic Modulus Values

Materials available on site for the construction of roads is derived from borrow pits or the pit itself. Borrow pit material comprises generally ferricrete and may be classified (following TRH14) as G4-G6. Selection criteria for these materials were analysed in terms of material grading, Atterberg limits, CBR, swelling and field compaction characteristics in order to assign target effective elastic modulus values to these materials. It was found that the modal material classification (ignoring in-situ material) is that of a G5-G6 gravel or low quality gravel where local mine ferricrete is used. To reduce the requirements for testing materials and to enhance the practical application of the mechanistic design method, it is prudent to adopt blanket modulus values where these, or other essentially similar material types are encountered. A modulus range of 150-200MPa is 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. These values are slightly lower than typical published values, thereby accommodating local deviations from the standard material classification. Values for the modulus of the in-situ sub-grade material are very much site and material specific and range from 17MPa to 388MPa and often exhibit stress softening. Dump rock material, consisting of selected sandstone or parting should be assigned a target effective elastic modulus value of 3000 MPa.

Whilst the empirical relationship proposed for determining the seed value for the effective elastic modulus for the mechanistic model could be advanced as a means of determining modulus values for insitu material, although some trend is evident, the confidence limits calculated for the relationship are large and a solution within 80% confidence extends over two decades. The associated standard error of estimate is 0,487 and R^2=68%. It is concluded that it is difficult to motivate for the existence of a direct relationship between effective elastic modulus and DCP penetration rate due to the very different testing techniques employed to derive different characteristic parameters for the same material. Where a modulus value is required for pavement layer modelling, the use of DCP probe derived CBR values in conjunction with published data provide the most tractable approach to ascertaining suitable modulus values for this material.

8.5 Recommended Mechanistic Design Procedure

Recommendations regarding the structural design of surface mine haul roads are 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, thereby reducing deflections (and consequent deformation) in the lower layers to a minimum. Using this approach, a reduced structural thickness was realised without the attendant deformation and reduction in structural performance that would otherwise be evident without a rock layer.

The design criteria derived from the mechanistic analysis of existing haul roads was used to complete a comparative structural design for a road recently constructed at Kleinkopje Colliery. For comparative purposes, two design options were considered; the AMCOAL design based on the CBR cover curve design methodology, as constructed by site contractors and the mechanistically designed optimal equivalent. Finally, the cost implications of the optimal design were analysed.

The optimal design incorporated a 200mm ferricrete wearing course layer with an effective elastic modulus of 150MPa and a 500mm layer of selected rock with an effective elastic modulus of 3000MPa constructed upon in-situ material with an effective elastic modulus of

85MPa. The structure was subjected to a 429kN dual rear wheel load and a 630kPa contact stress. It was seen that no excessive vertical compressive strains were generated in the structure, primarily due to the support generated by the shallow rock layer. Maximum surface deflections were approximately 2mm, reducing to 1,52mm in the in-situ material at a depth of 700mm. Deflections at a similar depth for the CBR based design in the in-situ material (800mm) were reduced to 1,43mm (compared with 2,02mm). The proposed optimal design thus provides an improved structural response to the applied loads than does the thicker CBR based design and, in addition, does not contravene any of the proposed design criteria for the particular performance index and traffic volume used in the analysis. .

A cost comparison of the two designs was compiled based on contractor tender unit costs for the construction of the 2A road at Kleinkopje. The variable costs taken into account were those of the volume and area of materials required and the associated costs of placing and compaction. By virtue of the reduced material volumetric and compaction requirements associated with the optimal design, a cost saving of R155 060, or 25% was realised. In terms of total construction cost (including preliminary and general costs), a 15% cost saving per kilometre was realised over the CBR-based design.

The optimal mechanistic design derived in the analysis was based on the particular in-situ material strength, applied load and required road performance (at a particular traffic volume) characteristics. If the type of truck changes, or the required performance index or tonnage hauled on the road, these can be modified in the analysis itself according to the proposed relationship between maximum strain and traffic volume/performance. In this respect the mechanistic design methodology and catalogue of values is transferable between sites which exhibit construction materials or traffic volumes within the inference space of the data analysed.

CHAPTER 9
QUANTIFICATION OF PAVEMENT FUNCTIONAL PERFORMANCE

9.1 Introduction

From the review of the current state of mine haul road functional design it was found that all existing specifications for mine haul road wearing course selection referred to only a limited number of selection variables and, in addition, have not been assessed in terms of their reliability and acceptability in practice. Since no evidence exists to suggest any of them are performance related the need was identified 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 and characterising material performance.

This chapter describes the development of a qualitative functional performance assessment methodology, based on typical road defects reported for public unpaved roads and modified and supplemented by defects reported by mine personnel. Initially, the functional performance evaluation criteria of degree and extent are introduced prior to a description of each haul road functional defect identified previously. Each defect is introduced in terms of its likely mode of formation and impact on haul road functionality, following which specific defect degree scores are described. The 12 month performance monitoring program is described and the data generated from each mine test site previously identified are summarised in terms of individual and total defect score variation with time, traffic volume and road maintenance activities. Using the material classification parameters analysed in Chapter 3.3, a preliminary estimation is made of the likely influence of these parameters on individual defects. This aspect is pursued in more detail in the following Chapter in which these results will then be used to indicate which material classification properties can be correlated statistically with a specific functional defect.

9.2 Functional Performance Evaluation Criteria

Since the functional performance of a haul road concerns the ability of the road to provide an economic, safe and vehicle friendly ride, a number of functional characteristics may be recognised which reduce the functionality of the road. These characteristics refer either to defects which occur on the road, the condition of certain elements of the road or indicators of road performance. The characteristics adopted for the visual evaluation of mine haul roads have been derived from recorded defects on unpaved public roads (Pienaar and Visser, 1992, CSRA TRH20, 1990) and the Standard Visual Assessment Manual for Pavement Management Systems (CSRA TMH9, 1990b), suitably modified to accommodate the requirements of mine haul road operators.

The condition of the pavement is considered from the point of view of the road user and incorporates appraisal in terms of those characteristics that affect the quality of travel. The assessment is entirely qualitative and to reduce the amount of subjectivity involved, distress characteristics are recorded in terms of degree and extent. The degree of a particular type of distress is a measure of its severity. Since the degree of distress can vary over a pavement test section, the recorded degree should give the best average assessment of a particular type of distress over the test section. Degree is indicated by a number where Degree 1 indicates the first evidence of a particular type of distress and Degree 5 very severe distress. The general descriptions of degree for each type of distress evaluated are presented in the following sub-sections, based on the general description of degree classification (following TMH9) given in Table 9.1.

The extent of distress is a measure of how widespread the distress is over the test section. Extent is indicated by a number where Extent 1 indicates an isolated occurrence and Extent 5 an extensive occurrence of a particular type of distress. The descriptions of extent are not associated with a specific functional defect and the general description of extent (following TMH9) as given in Table 9.2 is applied in assessing the extent of any defect. The rating of extent is applied only to those defects related to the wearing course material. Defects relating to formation and function (drainage, erosion and skid resistance) are analysed only in terms of degree.

Table 9.1 General Description of Degree Classification (following CSRA TMH9, 1990b)

DEGREE	SEVERITY	DESCRIPTION
0	-	No distress visible
1	Slight	Distress difficult to discern and only slight signs visible
2	Between slight and warning	Easily discernible distress but of little immediate consequence
3	Warning	Distress is notable with respect to possible consequences - start of secondary defects
4	Between warning and severe	Distress is serious with respect to possible consequences. Secondary defects have developed and/or primary defect is serious
5	Severe	Distress is extreme with respect to possible consequences. Secondary defects are notable and/or primary defect is extreme

Table 9.2 General Description of Extent Classification (modified following CSRA TMH9, 1990b)

EXTENT	DESCRIPTION
1	Isolated occurrence, less than 5% of road affected.
2	Intermittent occurrence, between 5-15% of road affected.
3	Regular occurrence, between 16-30% of road affected.
4	Frequent occurrence, between 31-60% of road affected.
5	Extensive occurrence, more than 60% of the road affected.

9.2.1 Defect Description and Rating

The general characteristics of each type of haul road defect assessed in the evaluation of haul road functionality are presented in the following sub-sections, together with the individual ratings for degree of defect based on the general description of degree classification (following TMH9) given in Table 9.1.

9.2.1.1 Potholes

Potholes are defined for the purposes of visual assessment as any depression in the road surface that affected the roughness of the road, other than corrugations and rutting. Origins of the potholes observed in mine haul roads were mostly (but not exclusively) traffic induced and occurred in the wheel paths, arising from;

- Maintenance operations (blading) plucking large oversize stones from the wearing course, leaving small, deep depressions in the road.
- The disintegration of highly cracked roads (a secondary defect).
- Local structural failure, usually evidenced as a larger size depression arising from compaction and/or shear in the subgrade.
- The ponding of either rain water or water used for dust allaying purposes in previously formed depressions. Water entering the wearing course in this manner weakens the material and thus propagates the hole.

The severity of the potholes were rated according to the classification in Table 9.3 which combines aspects of both physical size and the impact on the road user.

9.2.1.2 Corrugations

Corrugations are one of the major factors which cause excessive roughness on unpaved roads. They may either be in the form of "loose" or "fixed" corrugations and are thought to occur as a result of the forced oscillation of a vehicle suspension resulting in the kick-back of non-cohesive wearing course material, followed by compression and redistribution of the wearing course as the wheel makes contact with the road. (Heath and Robinson, 1980). Only fixed corrugations were regularly seen at some test site locations and it is hypothesised that the combination of low vehicle speed (20-40km/h) and large axle loads, together with regular watering for dust allaying purposes does not favour the existence of loose corrugations.

Low plasticity materials corrugate significantly, especially those with a high sand and gravel fraction. Regular blading of the haul roads contributes to the problem since material at the roadside is generally lacking in binder when spread over the road, but the action of the heavy trucks, their speed and the effects of regular watering and coal spillage ameliorates the problem to a certain extent. The concept of grading coefficient (G_c) and shrinkage product (S_p) are introduced in TRH20 (CSRA TRH20, 1990) as a means of identifying wearing course materials liable to certain functional defects and may be applicable to haul road as well as unpaved public road wearing course materials. The grading coefficient and shrinkage product are defined in Figure 2.1 from which it may be seen that materials liable to corrugate exhibit shrinkage products of less than 100.

The classification of the degree of corrugation defect is based on the road user's experience, both from the point of view of a light vehicle and for degree 4 and 5, from the point of view of a haul truck. The primary measure is one of defect avoidance due to the decrease in vehicle directional stability and braking efficiency associated with severe corrugations. Table 9.3 gives typical defect descriptions.

9.2.1.3 Rutting

Rutting is the formation of continuous longitudinal depressions in the wheel tracks. Whilst rutting may be caused by ravelling and gravel loss, the primary origin of rutting seen on mine haul roads is due to deformation (compaction) of highly cohesive wearing course materials (after ripping and blading) or subgrade (due to inadequate structural design). The latter is normally associated with wide, even ruts whilst narrow sharply defined ruts are indicative of inadequate structural strength in the vicinity of the wearing course material. Rutting is seen on most mine haul roads, due in part to the high axle loads and inevitable failure of the wearing course and the width of the road which allows consistent travel in demarcated ruts.

The classification of the degree of rutting defect is based on the road user's experience from the point of view of a haul truck. Depth is used as the primary measure of the defect as given in Table 9.3. Rutting only becomes a safety hazard when it affects the directional stability of a vehicle or causes ponding of water leading to further deformation of the wearing course.

9.2.1.4 Loose Material

Loose material or ravelling of the wearing course due to the action of traffic results in the formation of windrows in the centre of the road and alongside the travelled portion of the road. These features can significantly affect safety, skid resistance and lateral drainage. Ravelling is mainly attributed to a deficiency of fine material (and hence cohesion), a poor particle size distribution (gap grading) and inadequate cohesion and is exacerbated in the dry season. Materials with a grading coefficient greater than 34 and/or a shrinkage product of less than 100 are particularly prone to ravelling as seen from Figure 2.1.

The classification of the degree of loose material defect is based on a quantitative analysis of the depth of loose material on the road, derived from a study of unpaved public road performance (Paige-Green, 1989). Loose material refers primarily to wearing course material of a size less than 75mm. Since mine haul roads are used by both large haul trucks and smaller utility LDVs, the depth values adopted (40mm for degree 5) refer primarily to smaller vehicle safety although an increase in fuel consumption may also be evidenced by both light and heavy vehicles operating under the same conditions (Diack, 1994). Table 9.3 gives typical defect descriptions.

9.2.1.5 Dustiness

Dust is the fine fraction of the wearing course material (generally 2-75μm) released by the action of moving vehicles on the road, through a combination of wheel contact and turbulence. In addition to the wearing course material, the other factors influencing the degree of dust defect are a vehicle's aerodynamic shape, speed of travel, wind shear velocity, moisture condition, time elapsed since last maintenance, frequency of watering and use of palliatives.

Dust affects haul road functionality in terms of reduced visibility and thus the increased possibility of accidents (Sultan, 1976), increased wear on engine and mechanical components (Snyman, 1987) and the loss of wearing course fines. For unpaved public roads this can amount to between 25-33t/km/year (Jones, 1984). Most materials available for haul road construction will generate dust under the action of traffic, however, materials with a shrinkage product between 100 and 240 have been associated with a reduced dust defect on unpaved public roads (Paige-Green, 1989).

As a result of the large number of variables affecting the generation of dust, a visual classification system was developed for the degree of dust defect based on the road user's experience from the point of view of a haul truck travelling at 40km/h. Table 9.3 gives typical defect descriptions following Pienaar and Visser (1992).

9.2.1.6 Stoniness - Fixed in Wearing Course

The presence of large stones in wearing course materials can usually be controlled. Both the maximum size and the percentage thereof are important considerations. Excessive stoniness may lead to a number of primary and secondary defects in addition to that of an unnecessarily rough road;

- The formation of potholes (due to grader plucking stone out of road) or the formation of ridges (as grader blade bounces over the stone)

- Poor compaction of the wearing course in the vicinity of the stones, leading to potholes or ravelling

The classification of the degree of stoniness (fixed) defect is based on a qualitative estimation of the road user's experience from the point of view of a light vehicle (degree 1-4) and a haul truck (degree 5). Table 9.3 gives typical defect descriptions.

9.2.1.7 Stoniness - Loose on Road

Loose stones in the context of mine haul roads refer to stones larger than 75mm diameter occurring on the running surface. They may be generated from the wearing course material as described in section 9.2.1.6 and lead to excessive roughness, a reduction in safety due to stones being ejected from the edge of moving tyres and possible tyre damage, especially in wet conditions.

The classification of the degree of stoniness (loose) defect is based on a quantitative estimation of the areal extent of loose stones (derived from the wearing course) on the running surface. Table 9.3 gives typical defect descriptions.

9.2.1.8 Cracks

Cracks on unpaved roads are classified as a minor defect (CSRA TRH20, 1990), giving rise mostly to secondary defects such as loose material and potholes. Three specific types of cracking defect are assessed, namely;

- Longitudinal

  These are line cracks running longitudinally along the pavement, usually in the central (untrafficked) portion of the road. Although these cracks are not normally formed by traffic, the action of traffic and an associated lack of maintenance can lead to crocodile cracking in the wheel paths.

- Slip

  These cracks are related to the movement of the road structure (typical of fill areas) and to horizontal movement of the base layer over the underlying layers and occur as crescent shaped cracks, leading to large, shallow potholes on the edges of roads. On mine haul roads they are also seen in the centre of the road due to deformation of the wearing course under the shearing action of haul trucks.

- Crocodile

  Crocodile cracking may occur as a result of traffic induced fatigue of the wearing course or as a result of the plasticity of the material being too high. It is most often seen in the dry season and as cracks they may eventually link to form a crocodile skin pattern which may generate secondary pothole and loose material defects.

The classification of the degree of cracking defect (for each type) is based on the standard TRH6 (NITRR TRH6, 1985) method and descriptions which adapt well to the description of unpaved road cracking defects. Table 9.4 gives typical defect descriptions for each type of cracking.

9.2.1.9 Skid Resistance (Wet and Dry)

The skid resistance of a road in both its wet and dry state is an important safety consideration. The classification scheme adopted for wet and dry skid resistance defect is based on a quantitative and qualitative analysis of those factors affecting skid resistance, namely;

- Quality of wearing course material (plasticity index, CBR)
- Proper geometric construction of road (including camber and drainage)
- Amount of loose material present on road

Wearing course materials with a shrinkage product greater than 365 tend to be slippery in wet conditions due to the presence of an excessive amount of fine material (CSRA, TRH20,

Table 9.3 Classification of the Degree of Haul Road Defects

CHARACTERISTIC	DESCRIPTION				
	Degree 1	Degree 2	Degree 3	Degree 4	Degree 5
Potholes	Surface is pock marked , holes < 50mm diameter.	Potholes 50-100mm diameter.	Potholes 100-400mm diameter and influence riding quality.	Potholes 400-800mm diameter, influence riding quality and obviously avoided by most vehicles.	Potholes >800mm diameter, influence riding quality and require speed reduction or total avoidance.
Corrugations	Slight corrugations, difficult to feel in light vehicle.	Corrugations present and noticeable in light vehicle.	Corrugations very visible and reduce riding quality noticeably.	Corrugations noticeable in haul truck and causing driver to reduce speed.	Corrugations noticeable in haul truck and causing driver to reduce speed significantly.
Rutting	Difficult to discern unaided, <20mm.	Just discernable with eye, 20-50mm.	Discernable, 50-80mm.	Obvious from moving vehicle, >80mm.	Severe, affects direction stability of vehicle.
Loose material	Very little loose material on road, <5mm depth.	Small amount of loose material on road to a depth of 5-10mm.	Loose material present on road to a depth of 10-20mm.	Significant loose material on road to a depth of 20-40mm.	Considerable loose material, depth >40mm.
Dustiness	Dust just visible behind vehicle.	Dust visible, no oncoming vehicle driver discomfort, good visibility.	Notable amount of dust, windows closed in oncoming vehicle, visibility just acceptable, overtaking difficult.	Significant amount of dust, window closed in oncoming vehicle, visibility poor.	Very dusty, surroundings obscured to a dangerous level.
Stoniness - fixed in wearing course	Some protruding stones, but barely felt or heard when travelling in light vehicle.	Protruding stones felt and heard in light vehicle.	Protruding stones influence riding quality in light vehicle but still acceptable.	Protruding stones occasionally require evasive action of light vehicle.	Protruding stones require evasive action of haul truck.
Stoniness - loose on road	Occasional loose stone (>75mm diameter), $<2/m^2$	Some loose stone, $2\text{-}4/m^2$	Loose stone $4\text{-}6/m^2$, occasional discomfort felt.	Considerable loose stone on surface, $>6/m^2$, reducing riding quality.	Large amounts of loose stone causing significant reduction in riding quality.

Table 9.3 Classification of the Degree of Haul Road Defects (continued)

CHARACTERISTIC	DESCRIPTION				
	Degree 1	Degree 2	Degree 3	Degree 4	Degree 5
Cracks - longitudinal	Faint cracks discernable when surface cleaned.	Distinct, mostly closed, easily discernable when walking.	Distinct, mostly open, discernable from vehicle.	Open cracks, >3mm separation or wide open cracks >10mm separation, in travelling lanes.	Extensive open cracks, >3mm separation together with secondary cracks or extensive wide
Cracks - slip	Faint cracks discernable when surface cleaned.	Distinct, mostly closed, easily discernable when walking.	Distinct, mostly open, discernable from vehicle.	Open cracks, >3mm separation or wide open cracks >10mm separation, in travelling lanes.	Extensive open cracks, >3mm separation together with secondary cracks or extensive wide open cracks >10mm separation, in travelling lanes.
Cracks - crocodile	Very faint cracks in wheel path.	Faint cracks discernable when walking, closed.	Distinct cracks upto 2mm wide, no apparent deformation.	Open cracks (>2mm) with some deformation and/or spalling of cracked areas.	Open cracks with severe deformation and/or spalling of edges.
Skid resistance - wet	Wearing course material of good quality, road properly cambered, little loose material present.	Wearing course strength and PI acceptable, road cambered, loose material acceptable.	Wearing course strength low, PI fairly high, unsatisfactory camber and loose material.	Wearing course strength low, PI high, water standing on surface when raining, loose material influences skid resistance significantly.	Wearing course strength very low, PI very high, road very slippery when wet, loose material reduces skid resistance unacceptably.
Skid resistance - dry	Wearing course material of good quality, road properly cambered, little loose material present.	Wearing course strength and PI acceptable, road cambered, loose material acceptable.	Wearing course strength low, PI fairly high, unsatisfactory camber and loose material.	Wearing course strength low, PI high, loose material influences skid resistance significantly.	Wearing course strength very low, PI very high, loose material reduces skid resistance unacceptably.
Drainage on road	Very little water accumulates on road, no surface erosion is evident.	Shallow depressions may retain water for a limited time, most water drains away rapidly.	water may be retained in ruts and potholes, some surface erosion evident.	Water retained over a significant portion of the road, surface erosion <50mm deep in channels.	Water ponding on road to depths >50mm and erosion channels deeper than 50mm.
Drainage at roadside	Side drains very effective, well shaped with no obstructions.	Slightly irregular, some loose debris or occasional erosion, road well above side drain level.	Drains irregular in shape, blocked or eroded, road above side drain level.	Drains irregular or eroded and blocked over >25% road length, road and side drain at same elevation.	Side drains deeply eroded or non existent along 75% of road length or road surface below side drain.

1990). Several of the factors associated with skid resistance have been previously assessed, thus dictating to a large extent the defect degree defined. Table 9.4 gives typical defect descriptions for each type of skid resistance.

9.2.1.10 Drainage (on Road and Roadside)

The main factor influencing on-road drainage is that of the cross-fall of the road (geometric design of road and efficiency of maintenance) together with the degree and extent of the other primary defects such as potholes, rutting, ravelling and loose material. Rainfall intensity and duration are also significant factors together with the amount of erosion the road experiences. Since it is difficult to separate individual factors, the classification scheme adopted involves a qualitative estimation of properties associated with drainage, ponding and erosion on the road surface. Roadside drainage defect is considered from the point of view of the likely drain performance in wet weather, together with its geometric design in relation to the road. These classification descriptions are given in Table 9.4 for both types of drainage analysed.

9.3 Performance Monitoring

In order to assess the utility of established performance related material selection guidelines for adoption in haul road design, the functional performance of a particular mine haul road test site was analysed in terms of the wearing course, formation and function defects described previously. Figure 9.1 shows the assessment form used together with the additional dependant and independent variables outlined in Chapter 3.3.

Performance monitoring was conducted for a period of 12 months from May 1994 at three test sites at each of Kriel, Kromdraai and New Vaal Collieries and two test sites at Kleinkopje Colliery. Whilst climate as a variable was discounted in the experimental design since the majority of existing strip coal mines are situated in the climatic region $2<N<5$ it is nevertheless important to determine whether or not the period of assessment can be taken

UNIVERSITY OF PRETORIA
DEPARTMENTS MINING AND CIVIL ENGINEERING
HAUL ROADS RESEARCH PROJECT

FUNCTIONAL PERFORMANCE ASSESSMENT

MINE : ____________
DATE : ____________
ROAD NUMBER : ____________
CHAINAGE : ____________
WEARING COURSE MATERIAL : ____________
WEARING COURSE DEPTH : ____________
MOISTURE CONDITIONS WET MOIST DRY

DAYS SINCE LAST MAINTENANCE : ____________
TRAFFIC (t/DAY) : ____________
TRUCK TYPE(S) : ____________
AVERAGE VEHICLE SPEED : ____________
WEARING COURSE SAMPLE NUMBER : ____________
WATER SAMPLE NUMBER : ____________
PHOTOGRAPH NUMBERS : ____________

		DEGREE (MINOR – SEVERE) 1	2	3	4	5	EXTENT (SELDOM – FREQUENT) 1	2	3	4	5
POTHOLES											
CORRUGATIONS											
RUTTING											
LOOSE MATERIAL											
DUSTINESS											
STONINESS	- FIXED										
	- LOOSE										
CRACKS	- LONGITUDINAL										
	- SLIP										
	- CROCODILE										
SKID RESISTANCE	- WET										
	- DRY										

		V GOOD	GOOD	FAIR	POOR	V POOR
EROSION	- LONGITUDINAL DIRECTION					
	- CROSS DIRECTION					
DRAINAGE	- ON THE ROAD					
	- SIDE OF ROAD					

RIDING QUALITY ASSESSMENT

COMMENTS AND OBSERVATIONS

Figure 9.1 Functional Performance Assessment Recording Form as average in terms of long term mean rainfall for the region. Figure 9.2 presents the annual rainfall recorded at Clydsdale, Kriel, Landau and Witbank, representing the adjacent mines of New Vaal, Kriel, Kleinkopje and Kromdraai for the period May 1994-April 1995. The long term mean rainfall is also shown. Since rainfall over the period May 1995-April 1995 represented between 88% and 103% of the long term mean rainfall it may be concluded that the annual figures over the monitoring period are not significantly different from the long term mean.

The performance of unpaved roads is affected more by short term weather than long term climate. Thus periodic heavy showers or dry spells are more important when assessing functionality than are longer term trends. These short term effects are discussed in more detail later.

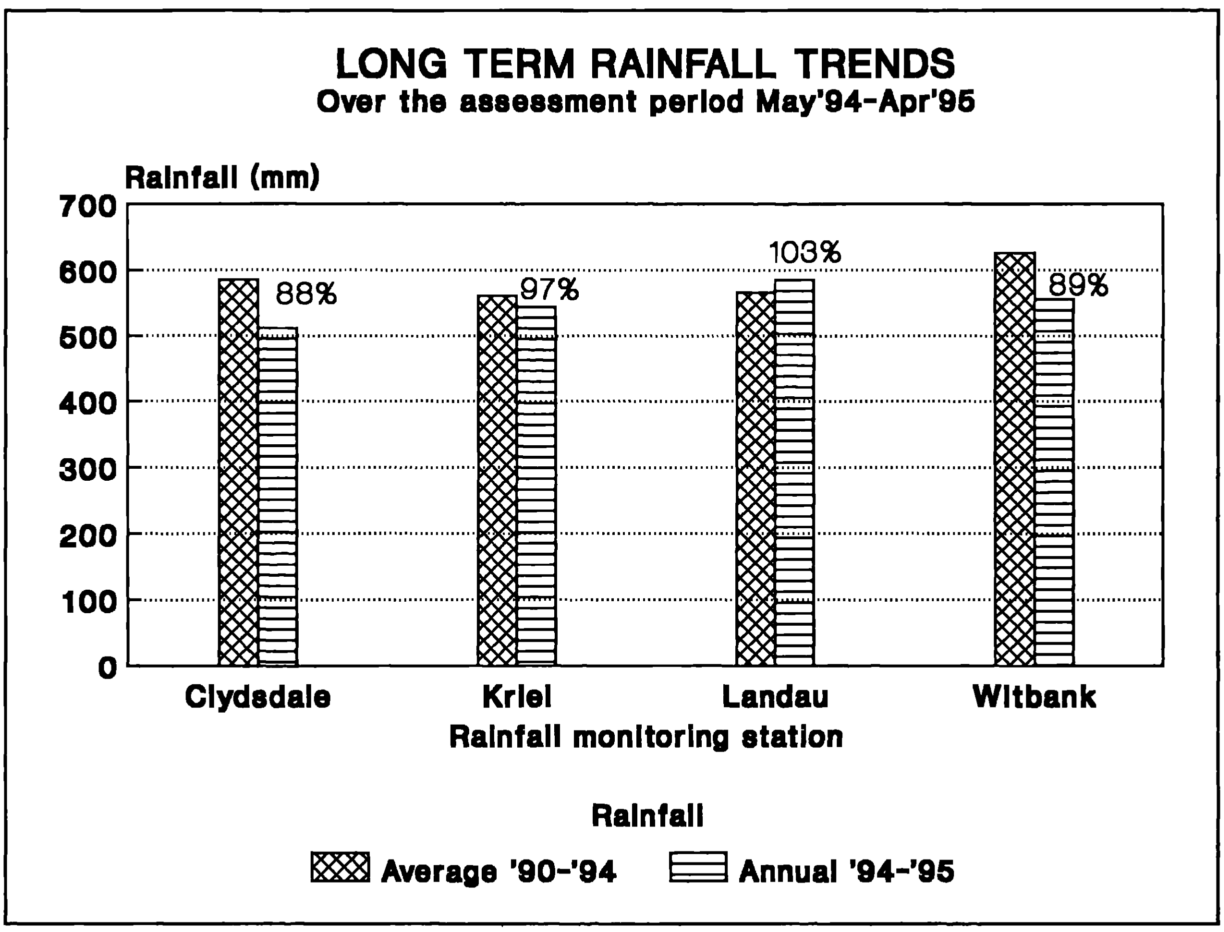


Figure 9.2 Long Term rainfall trends for Stations in the Vicinity of Mine Test Sites

The results of the functional performance assessment for each mine test site as envisaged in the experimental design, over the twelve month monitoring period (May 1994-April 1995) are presented below. Appendix F contains the data from the performance assessment and forms the basis of the following results.

9.3.1 Results of Performance Monitoring - Kriel Colliery

In the experimental design outlined in Chapter 3.3.2.1, three test sites were identified at Kriel Colliery. Their location is given in Figure 3.8 and summarised below.

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.

The wearing course material is sourced on the mine and is described as a dolerite, ferricrete and ash mixture for sites 1 and 2 (in the ratio 7:2:1) and a ferricrete sand for site 3. A G6 classification (following CSRA TRH14, 1985) is given to all sites. Although essentially similar in terms of the TRH14 classification, the material comprising the wearing course at site 2 exhibits a higher plasticity index and lower CBR values than the other sites. In addition, a greater proportion of fine material (<0,075mm) is present in this particular material mix.

Traffic levels encountered varied from an average of approximately 15 000t per day at site 1 and 3 to 6 000t per day at site 2. All sites experienced an increase in traffic from January 1995, sites 1 and 3 a 14% increase and site 2 a 17% increase. This combination of wearing course material variation and traffic does not enable the functional performance of the roads to be compared under various traffic levels. However, an insight into the comparative functional performance of the various wearing course materials and the effect of maintenance can be determined. As a precursor to this assessment, the performance of each site is summarised in the sections that follow.

Site 1

The performance of site 1 over the assessment period in terms of individual and average wet season, dry season and annual defect (the sum of each defect degree and extent product) scores is presented in tabular form in Appendix F1. Dustiness, loose material and rutting defects contributed the most to the total material defect scores (approx. 18%, 15% and 11% respectively). These defect scores are shown graphically in Figure 9.3 from which it is seen that although individual defect scores vary slightly, there is no obvious trend.

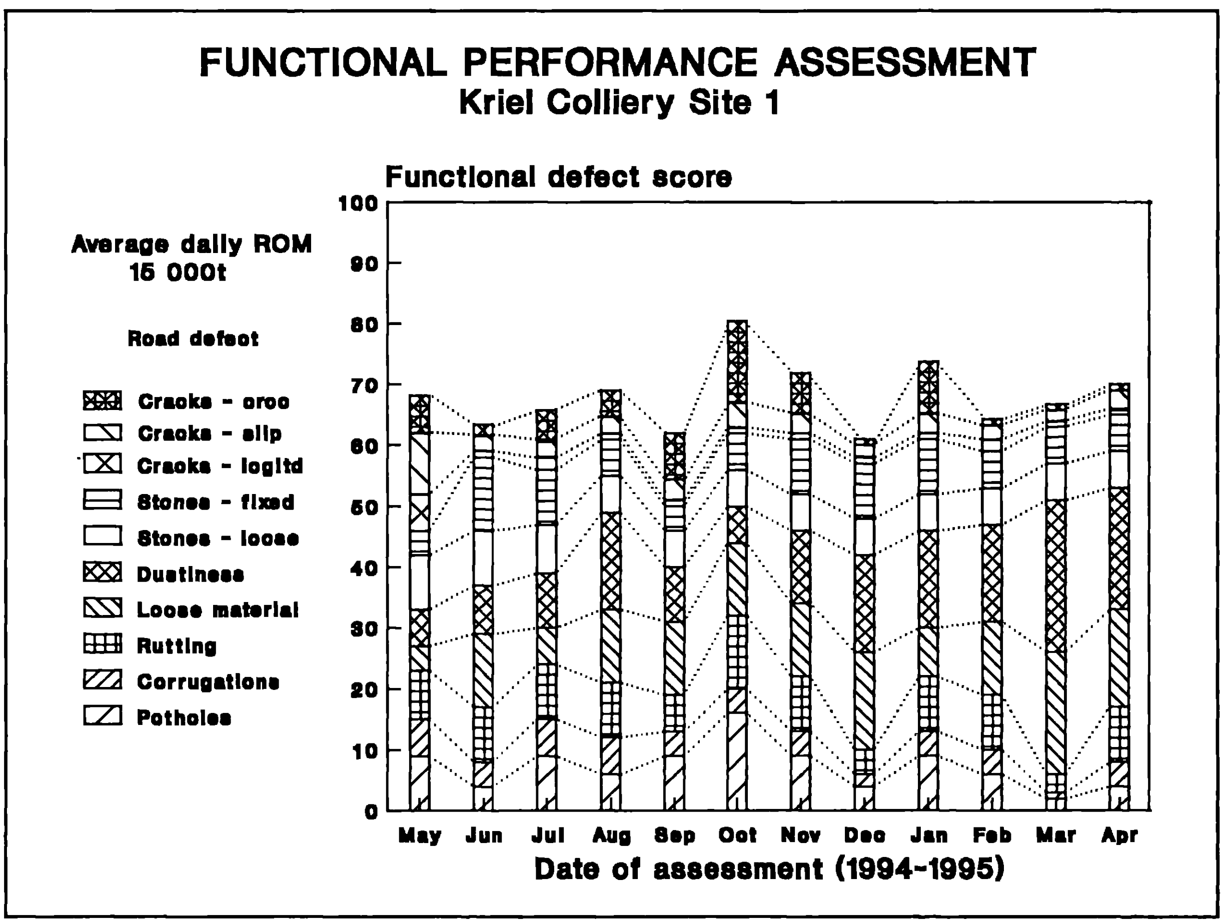


Figure 9.3 Functional Performance Assessment, Kriel Colliery Site 1

An additional 60mm wearing course material was added during June 1994, consisting mostly of ferricrete. This material was sourced from local mine borrow pits and in the absence of material testing, thought to be similar to the wearing course at site 3. The long term functional performance of site 1 is shown in Figure 9.4 in relation to the other sites at Kriel and the wet and dry season rainfall. It is seen that all three sites follow a similar pattern, albeit at different defect score levels and an increased sensitivity to rainfall, especially at site 2. This is indicative of a seasonal (rainfall associated) factor in the functionality of roads, especially in regard to an initial increase in defect scores with the onset of regular rain. Although not an objective of this part of the research program, this result implies that the type and level of maintenance carried out in winter and summer may vary and as such, with a change in the seasonal rainfall patterns there may not be any anticipation of the resultant modification in functionality.

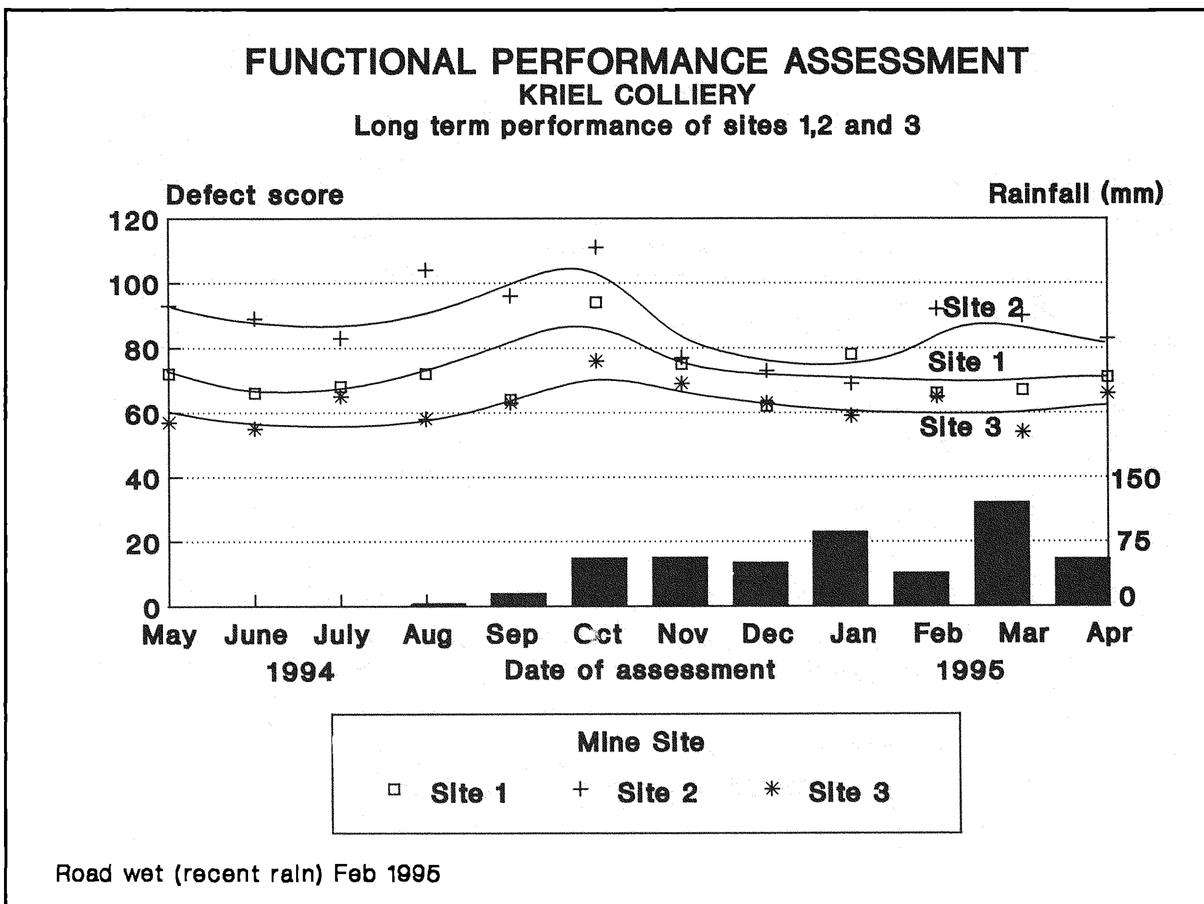


Figure 9.4 Long Term Performance Assessment, Kriel Colliery Sites 1, 2 and 3.

If the number of days since last maintenance is included in the analysis of defect score, a functionality trend becomes obvious as shown in Figure 9.5. There is a decrease in road defect scores immediately after maintenance takes place on the road, due to a decrease in high dust and loose material defect scores that occur immediately after blading, for between two and three days. Then follows a period of steadily increasing defect scores. Figure 9.6 illustrates this effect through consideration of the change in defect score between one and seven days after maintenace. For this particular site, an increase in pothole, corrugation, rutting and crocodile crack defects is seen. For the defects of loose material, dustiness and loose stones, initially high defect scores, immediately after maintenance, reduce and then increase as the number of days between maintenance increases.

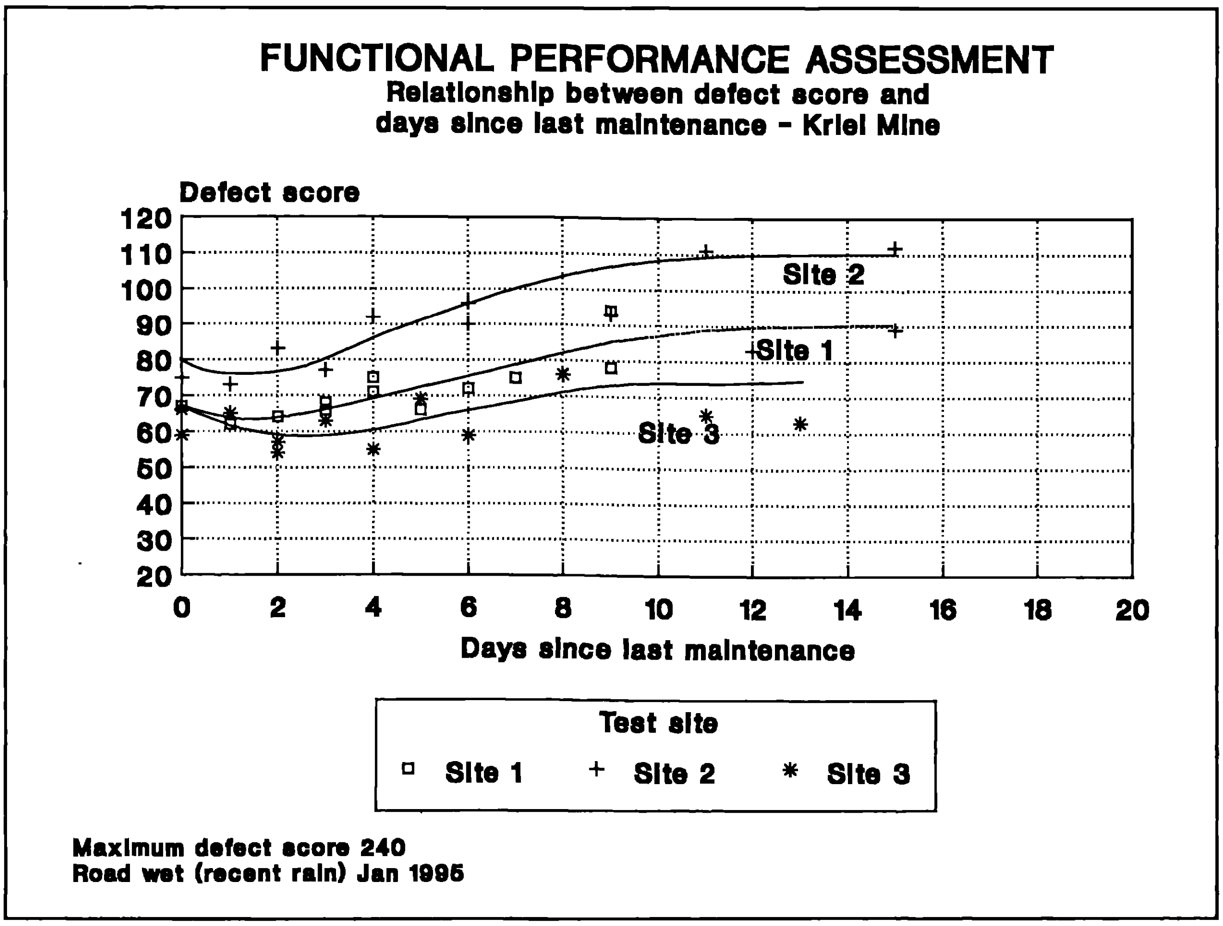


Figure 9.5 Effect of Maintenance on Defect Scores, Kriel Colliery Sites 1, 2 and 3.

No relationship between defect score and traffic levels can be determined from this data owing to the variation in wearing course material at each site. In addition, the structural performance of the various test sections is different (Thompson and Visser, 1994) and this

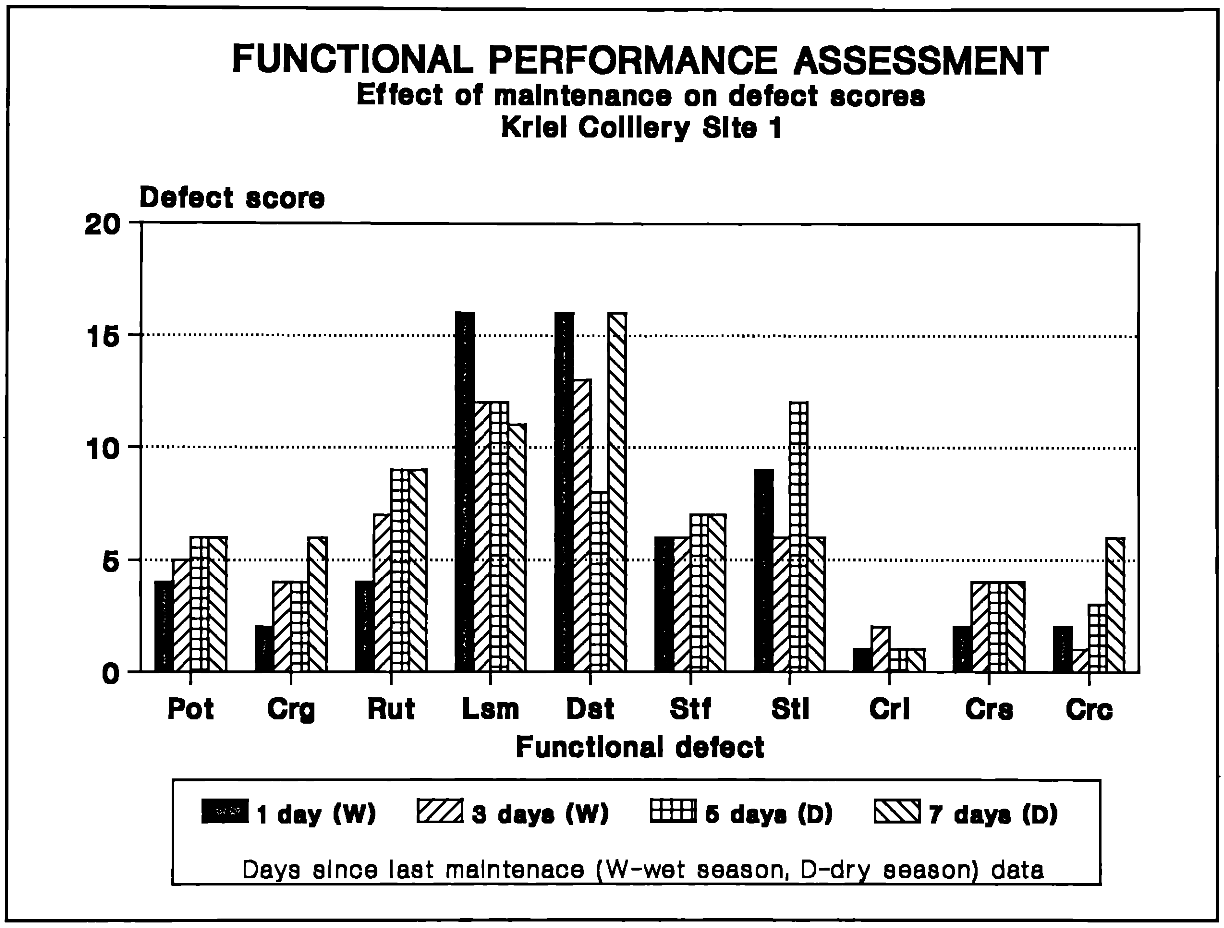


Figure 9.6 Effect of time since last maintenance on defect scores, Kriel Colliery Site 1.

leads to a decrease in functionality due to the effect of structurally induced defects on the overall functional performance rating. This is illustrated by the large slip crack defect score recorded in May 1994 at site 1 (prior to the addition of new wearing course material) and the formation of wide even ruts which is indicative of deformation in the lower pavement layers.

Figure 9.7 shows a general view of site 1 with the laden side of the road on the RHS. Although the site offered both level and grade (3,6%) sections, no significant difference in functional performance was noted except for slightly worse rutting on the laden side and crocodile cracking on the unladen grade section, probably due to the deceleration of the mine haul trucks coupled with a relatively plastic material. No excessive erosion of the wearing course was noted (along or across the road). Cracking of the wearing course material is shown in Figure 9.8 together with the presence of stones in the wearing course. During maintenance these stones lead to ridges being bladed into the road or, when removed, small

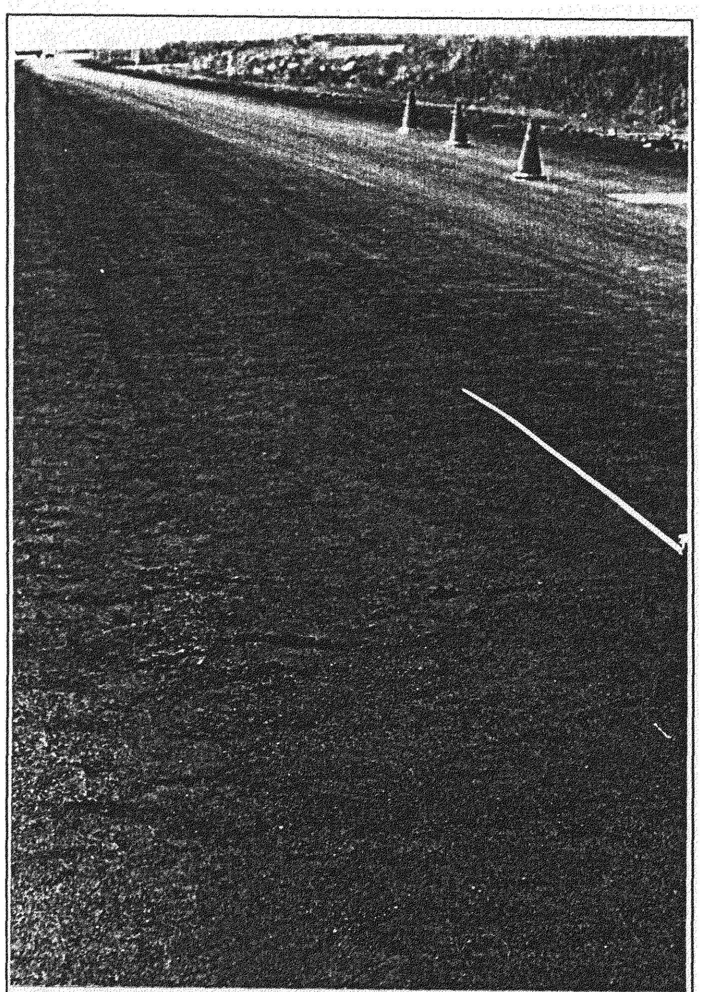


Figure 9.7 General View of Kriel Colliery Site 1, showing rutting and damage to wearing course.

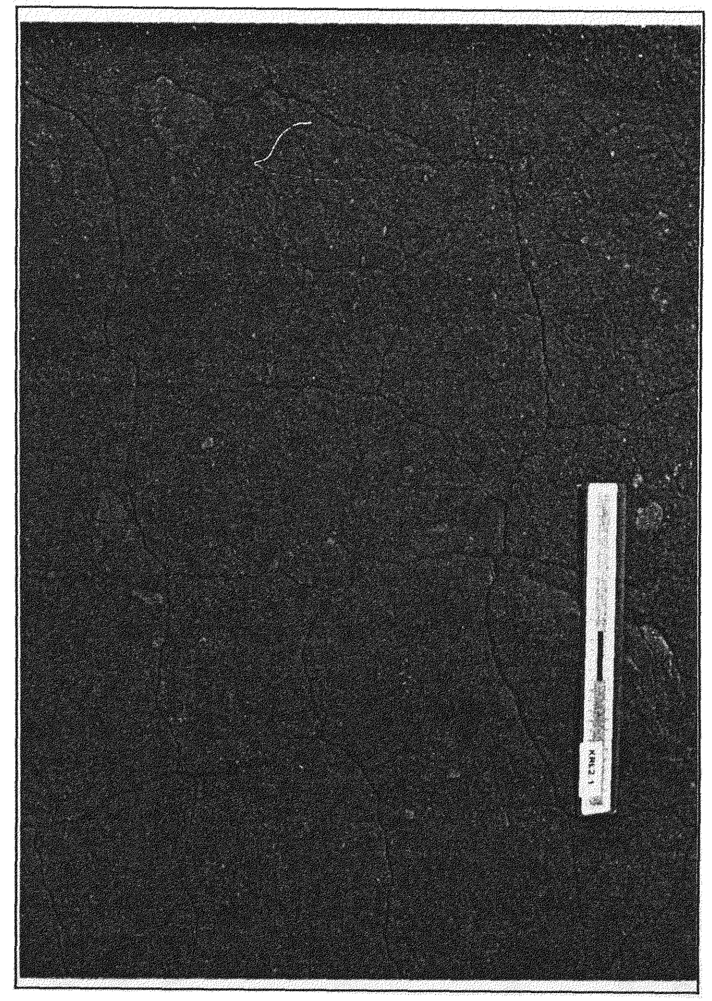


Figure 9.8 Crocodile cracking and large stones in wearing course, Kriel Colliery site 1.

potholes being formed. Wet and dry skid resistance average defect scores of 19 and 17 (using an extent score of 5) were recorded, the wet skid resistance score only being encountered after rain. The effect of watering the road to allay dust did not result in a significant wet skid resistance hazard since evaporation and absorption quickly removed excess water. The dry skid resistance defect was associated with small (<2mm) diameter ferricrete nodules on the road, recorded as loose material. Most of this loose material was seen to form windrows outside the wheel tracks, especially at the edge of the road.

<u>Site 2</u>

The performance of site 2 over the assessment period in terms of individual and average wet season, dry season and annual defect scores is presented in tabular form in Appendix F1. Rutting, dustiness and loose material were the major defects recorded (approx. 11%, 10% and 9% of total material defect score respectively). Although apparently smaller than those recorded for site 1, the average defect score for site 2 was in excess of 100 compared to a score of 72 for site 1. Figure 9.9 shows the relative defect scores graphically, again without any consideration of maintenance. The reduction in rutting defect recorded from November is attributable to the remedial work carried out by the mine to repair badly deformed sections of the road which were coincident with excessive rutting and corrugations. The other defects recorded remain similar (in terms of degree and extent), illustrating the effect of structural performance on functionality. From Figure 9.4 a similar long term performance trend to site 1 is seen, albeit with higher defect scores and a greater sensitivity to rainfall. From Figure 9.5, the effect of maintenance in reducing functional defects is seen together with a slightly lower rate of increase in defect scores after maintenance due to the lower traffic levels on this road. It may be inferred from the graph that beyond a maintenance interval of 10 days, the functionality of the road reaches a stable terminal condition. This condition will almost certainly be far below the required level of functional performance for the road. Figure 9.10 shows that the effect of maintenance on this road reduces most defect scores initially, although the corrugation defect is higher. This may be due to stones in the wearing course forming ridges and small poholes during blading.

A general view of Site 2 is shown in Figure 9.11. No differences in functionality were evident between laden or unladen sides of the road. There was more damage seen on

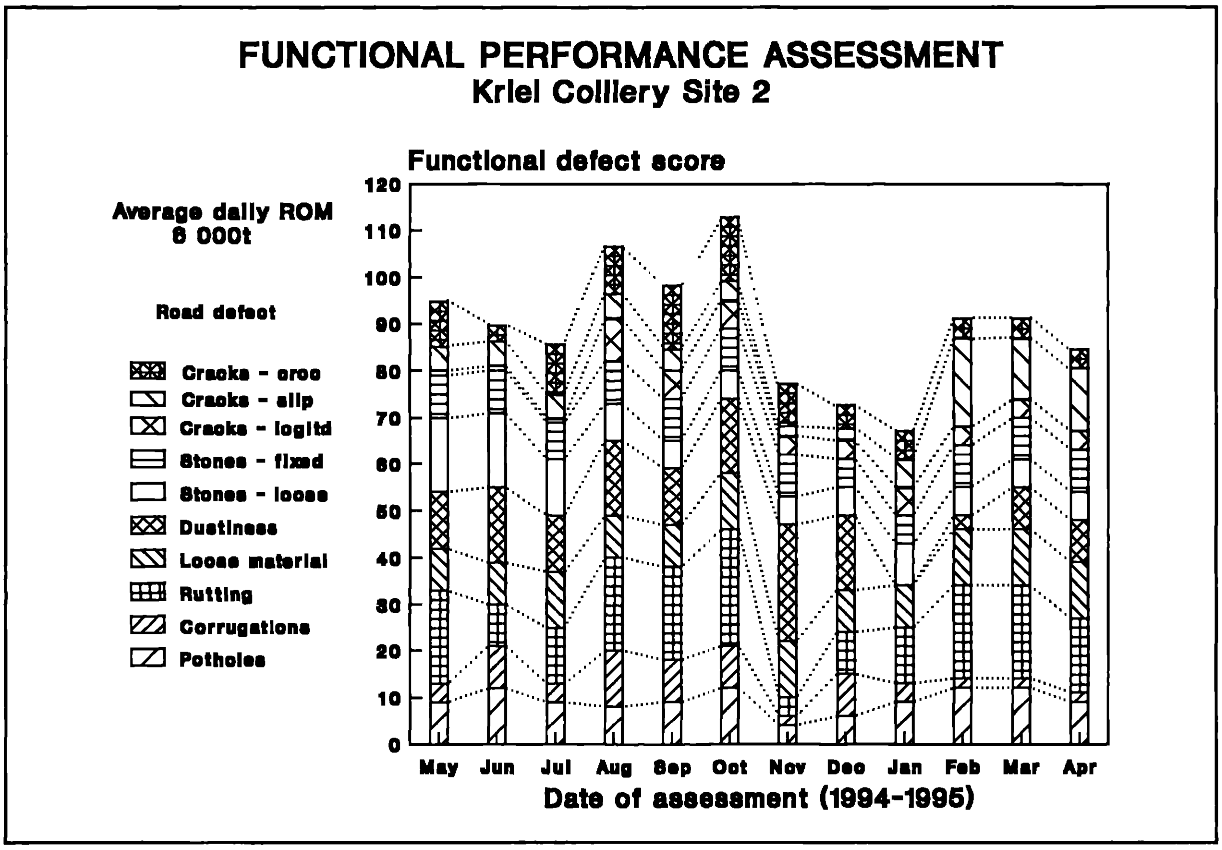


Figure 9.9 Functional Performance Assessment, Kriel Colliery Site 2.

curved sections of the road on the laden side, due primarily to the shearing action induced by the vehicle tyres and the high PI of the wearing course. Crocodile cracking was noted throughout the dry season (May-September 1994). This defect was much reduced in both degree and extent over the wet season, this again being indicative of a material with a high PI value. Figure 9.12 illustrates the combined effect of rainfall, poor roadside drainage, poor crossfall and inadequate structural performance on the functionality of the road, in terms of rutting, shearing and displacement of the wearing course and much reduced wet skid resistance. These defects may be associated with the low California Bearing Ration (CBR) of the material comprising the wearing course at this site. The problem may be exacerbated by the presence of a vlei in the vicinity of the road. The vlei area was pumped dry in September and October 1994 and this may be the reason for the short term decrease in defect scores recorded after October 1994.

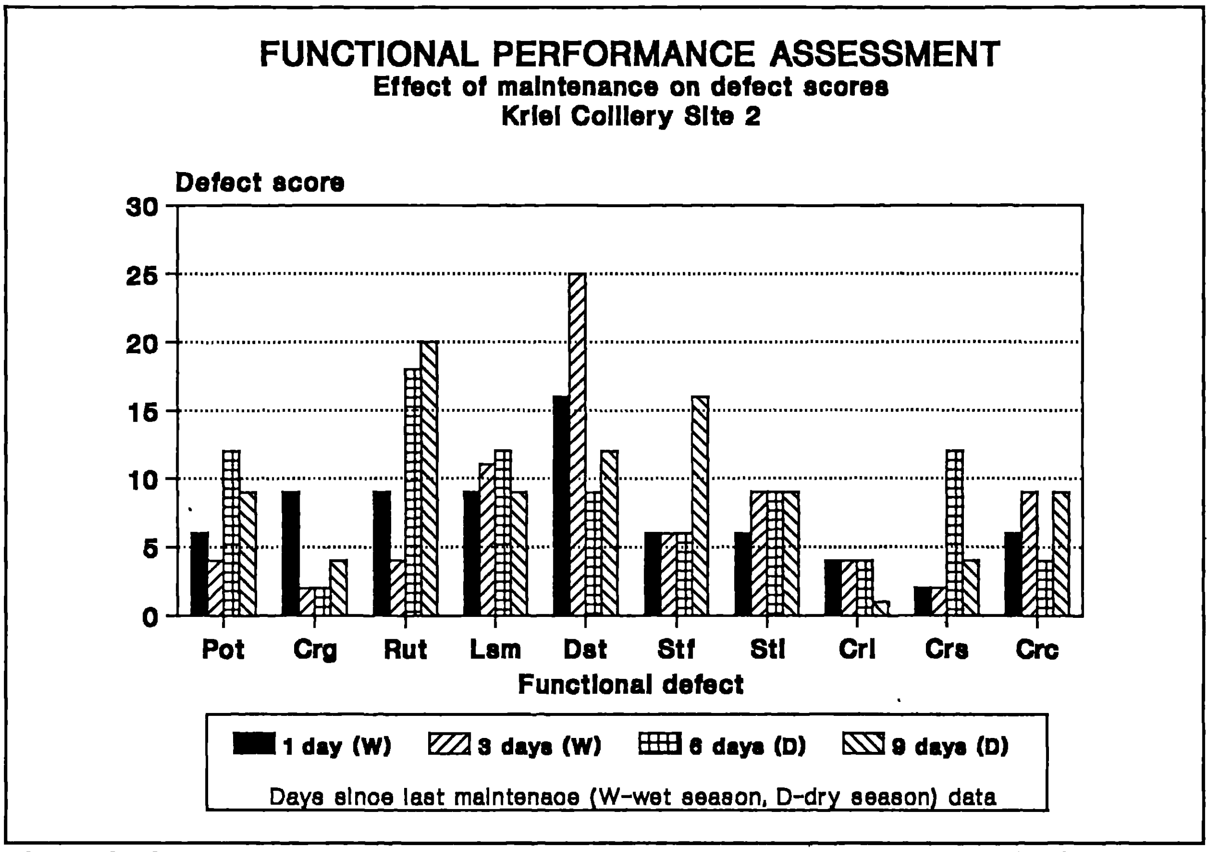


Figure 9.10 Effect of time since last maintenance on defect scores, Kriel Colliery site 2.

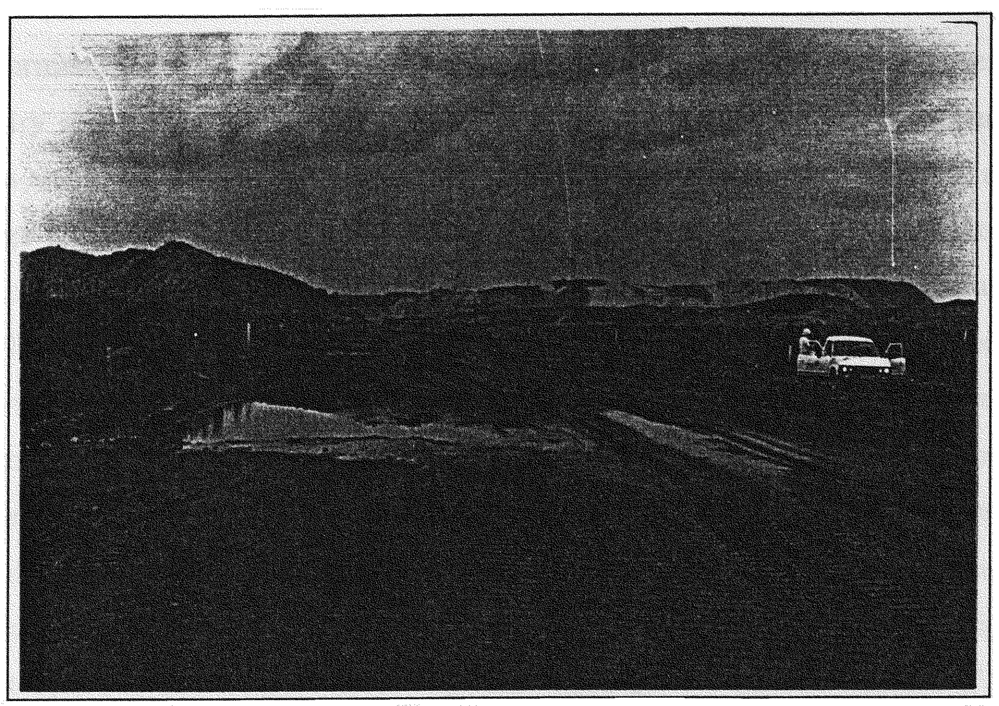


Figure 9.11 General View of Kriel Colliery Site 2.

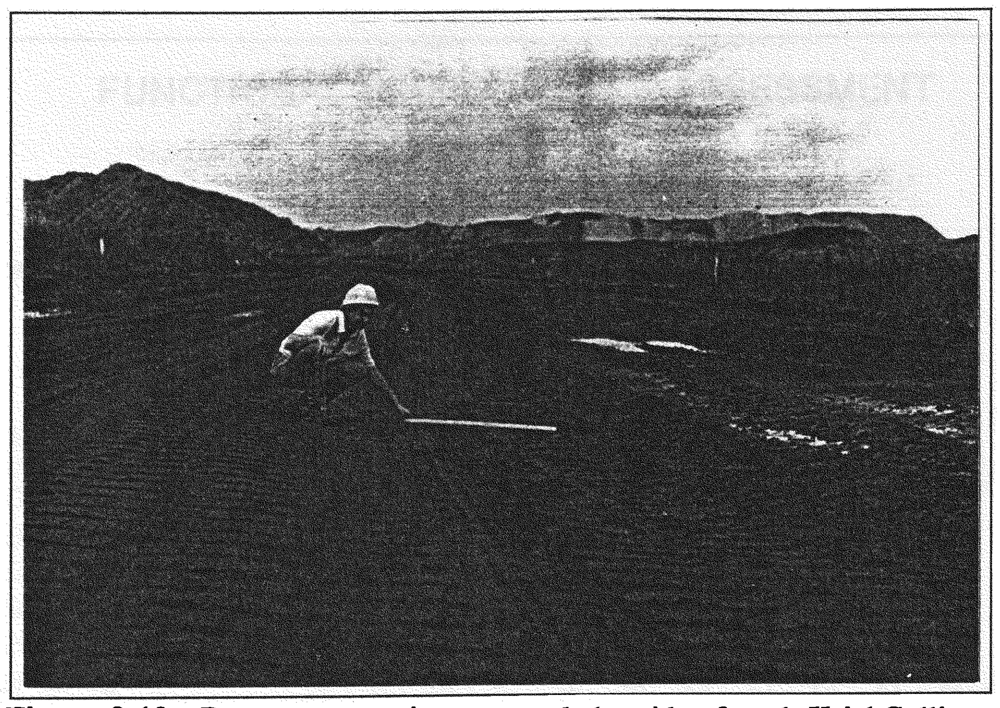


Figure 9.12 Damage to wearing course, laden side of road, Kriel Colliery Site 2.

Site 3

The performance of site 3 over the assessment period in terms of individual and average wet season, dry season and annual defect scores is presented in tabular form in Appendix F1. Dustiness and loose material were again the major defects reported (approx. 21% and 19% of average total material defect score of 62 respectively). Figure 9.13 shows the relative defect scores graphically. From Figure 9.4 the long term performance trend shows an almost constant level of functionality over the dry season, but as rainfall increases during the months of September and October 1994, the defect score increases. From January onwards, the defect scores again decrease to a similar level to that experienced over the dry season, hence it may be concluded that with the onset of rains there is an increase in defect scores which is only corrected through an increase in the frequency of maintenance, although the type of material used at this site is less sensitive to rainfall than those at sites 1 and 2. Figure 9.5 shows the effect of maintenance in reducing functional defects and a lower rate of increase in defect scores after maintenance. This can be ascribed to the superior structural performance of the road at this site together with the characteristics of the ferricrete wearing course material used.

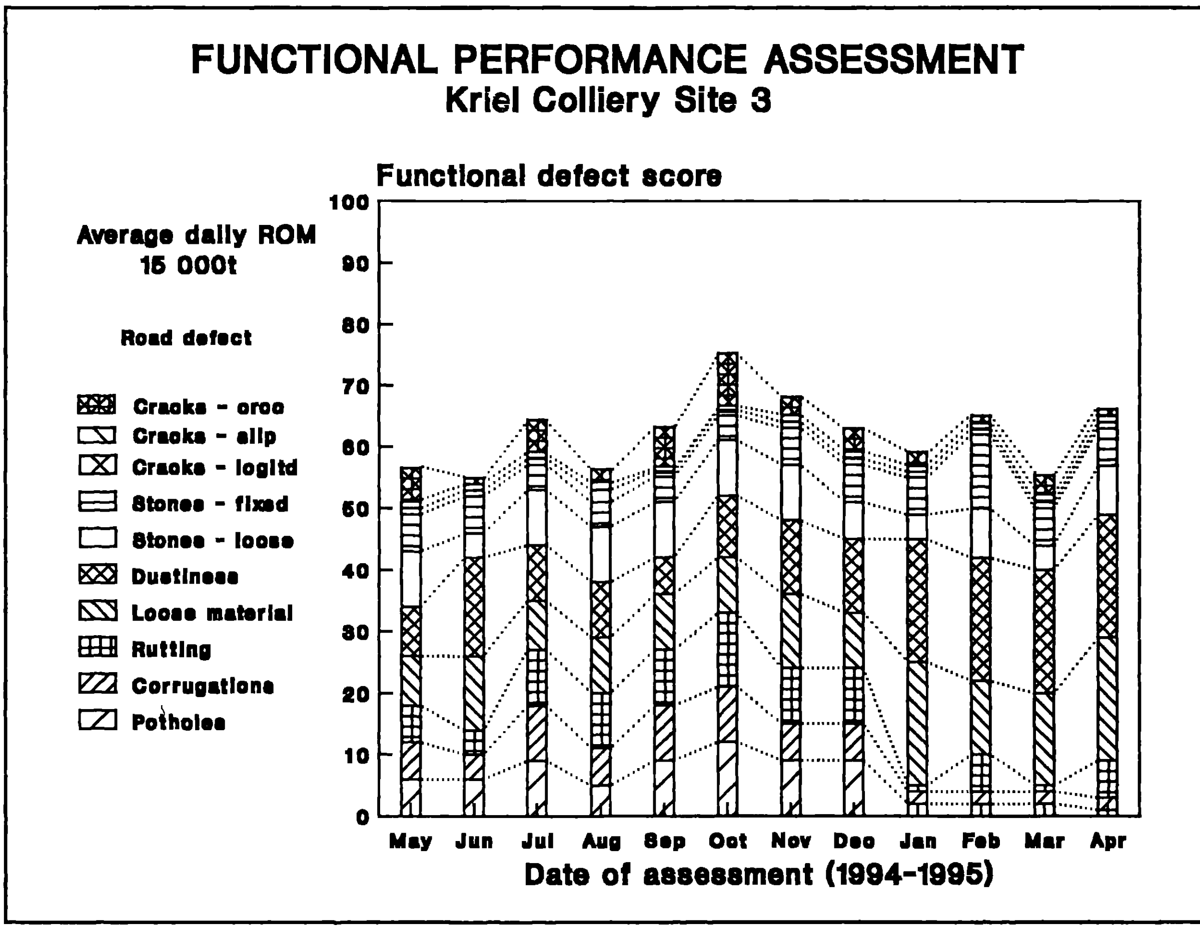


Figure 9.13 Functional Performance Assessment, Kriel Colliery Site 3

With regard to the effect of maintenance on individual defect scores, the defects of pothole, corrugation, rutting and crocodile cracking all increased with increasing interval between maintenance. Dust, loose material and loose stoniness defects all reduce after maintenance which reduces the overall rate of increase in defect score. The formation of a "blad" due to natural cementation of the local mine ferricrete was seen at this site which may explain the continued reduction in dust and loose material defect scores seen. Dry skid resistance defect scores are accordingly sensitive to the number of days since last maintenance, poor dry skid resistance is noted immediately after maintenance due to the presence of loose material on the road. Figure 9.14 shows a general view of site 3 illustrating a typical ferricrete "blad". As referred to in Chapter 4 and 5, this site exhibited superior structural performance due to the location of a stabilised layer immediately below the wearing course.

Figure 9.14 General View of Kriel Colliery site 3.

9.3.2 Results of Performance Monitoring - Kromdraai Colliery

In the experimental design outlined in Chapter 3.3.2.2, three test sites were identified at Kromdraai Colliery. Their location is given in Figure 3.9 and summarised below.

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.

The wearing course material is sourced on the mine and is as such similar for all three sites. A G7 classification (following CSRA TRH14, 1985) is given to sites 1 and 2 whilst site 3 receives a G6 classification by virtue of higher California Bearing Ratio (CBR) values. Traffic levels encountered varied from an average of approximately 15 000t per day at site 1 to 7 500t per day at sites 2 and 3. Site 3 is a more recent construction and although in operation since February 1994, traffic levels of 7 500t per day were only achieved from October 1994 onwards. This combination of circumstances enables the functional performance of the roads to be assessed under various traffic levels. As a precursor to this assessment, the performance of each site is summarised in the sections that follow.

<u>Site 1</u>

The performance of site 1 over the assessment period in terms of individual and average wet season, dry season and annual defect scores is presented in tabular form in Appendix F2. Loose material and dustiness defects contributed the most to the total material defect scores (approx. 20% for each). These defect scores are shown graphically in Figure 9.15 where it is seen that although individual defect scores vary slightly (excepting January 1995 assessment taken during wet weather, hence the low dust defect score), there is no obvious trend.

The long term functional performance of site 1 is shown in relation to the remaining sites at Kromdraai and the seasonal rainfall in Figure 9.16. If the variable of days since last maintenance is included in the analysis of defect score, a trend becomes obvious as shown in Figure 9.17. There is a decrease in defect scores immediately after maintenance takes place on the road due to a decrease in high dust and loose material defect scores as a result of blading, for between 2 and 3 days. Then follows a period of steadily increasing defect scores as dust, corrugation, rutting and cracking defect scores increase as shown in Figure 9.18. The relationship with traffic levels (tons/day) is also obvious when sites 2 and 3 are assessed in relation to site 1, the latter carrying twice the traffic volume as the other sites and, all other factors being equal, thus experiences an increased rate of deterioration.

Figure 9.19 shows a general view of site 1 with the loaded side of the road on the LHS. Although the site is slightly on grade (1,7%), no significant erosion of the wearing course

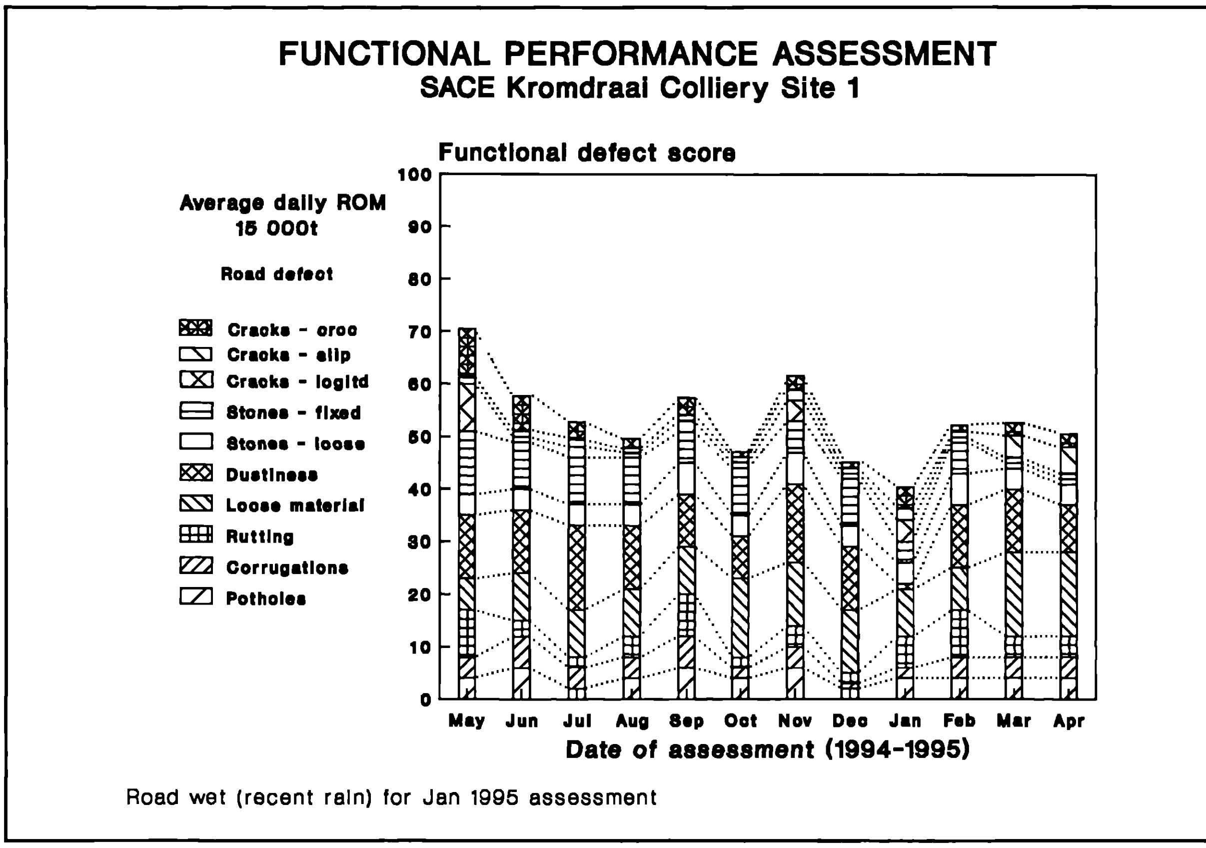


Figure 9.15 Functional Performance Assessment - Kromdraai Mine Site 1.

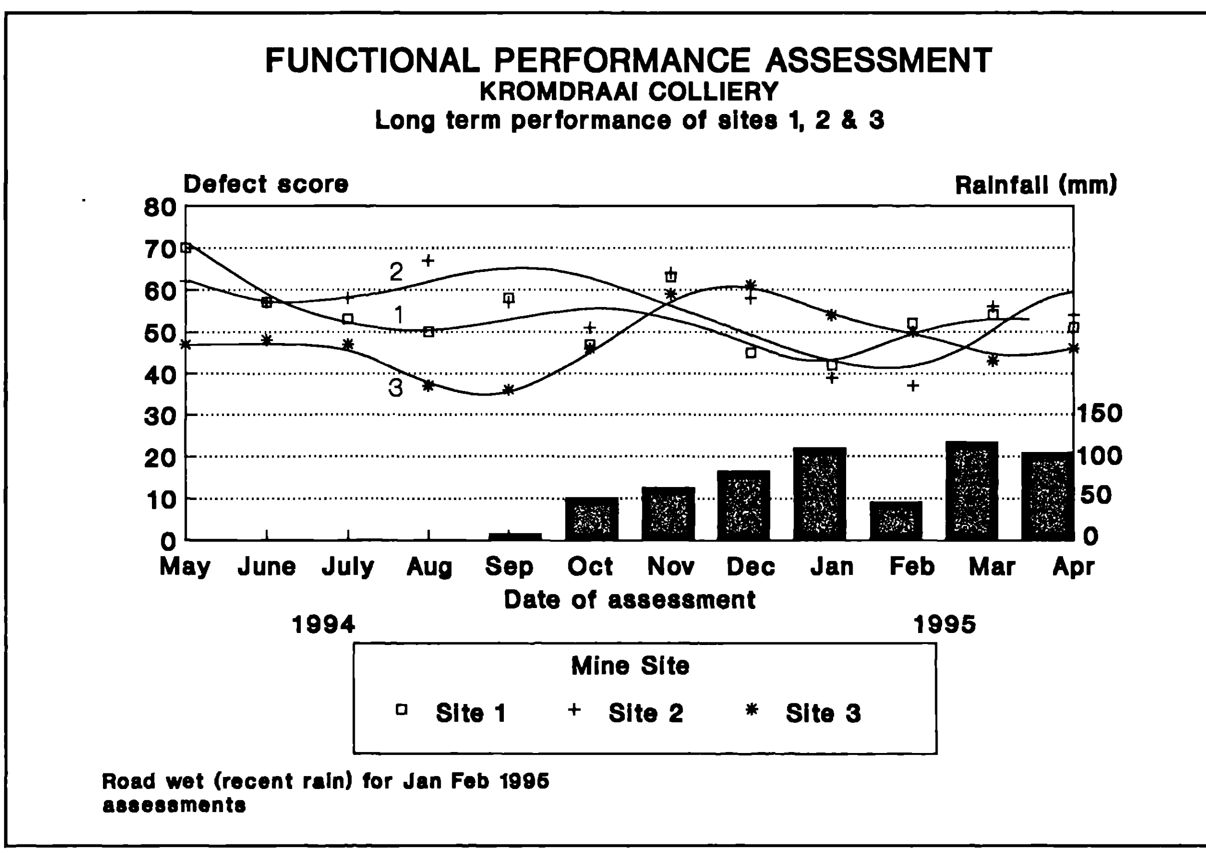


Figure 9.16 Long Term Performance Assessment of Sites 1, 2 and 3, Kromdraai Colliery

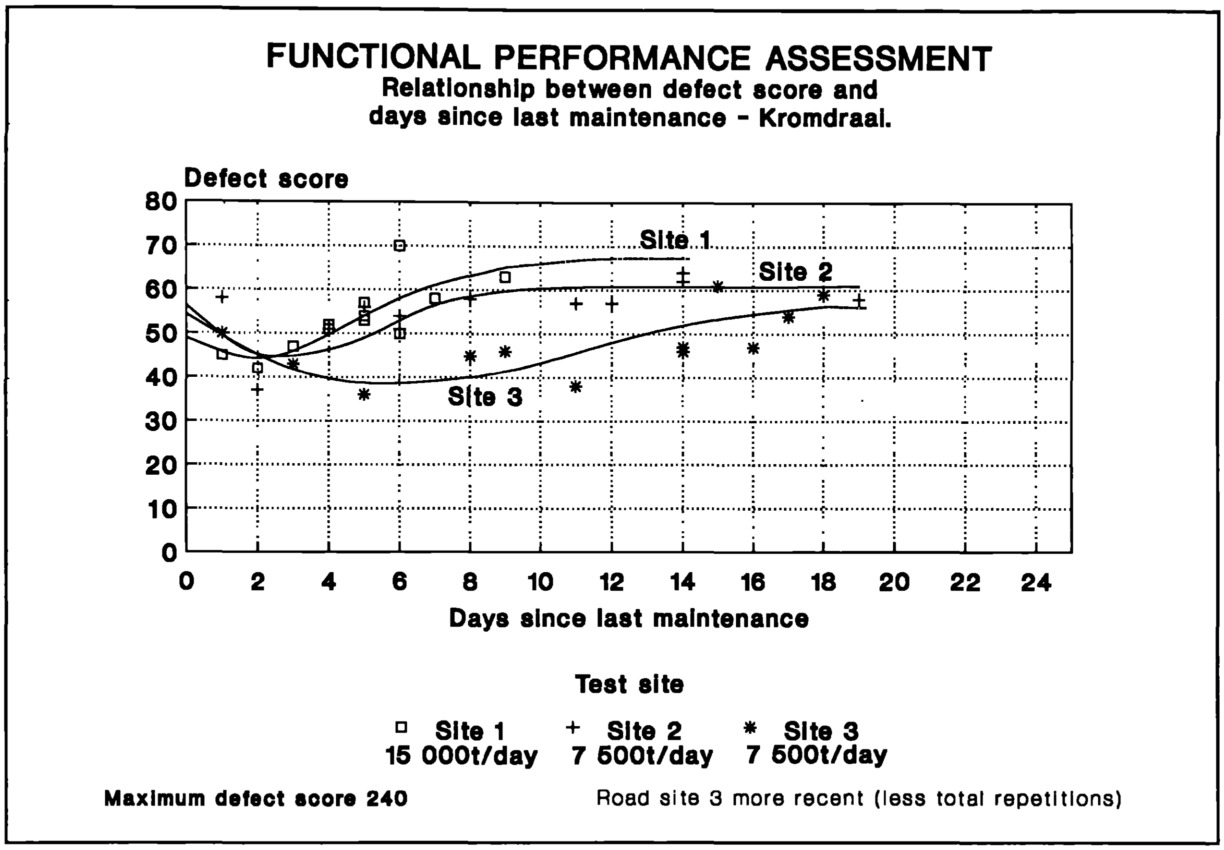


Figure 9.17 Effect of Maintenance on Defect Score - Kromdraai Colliery Sites 1, 2 and 3.

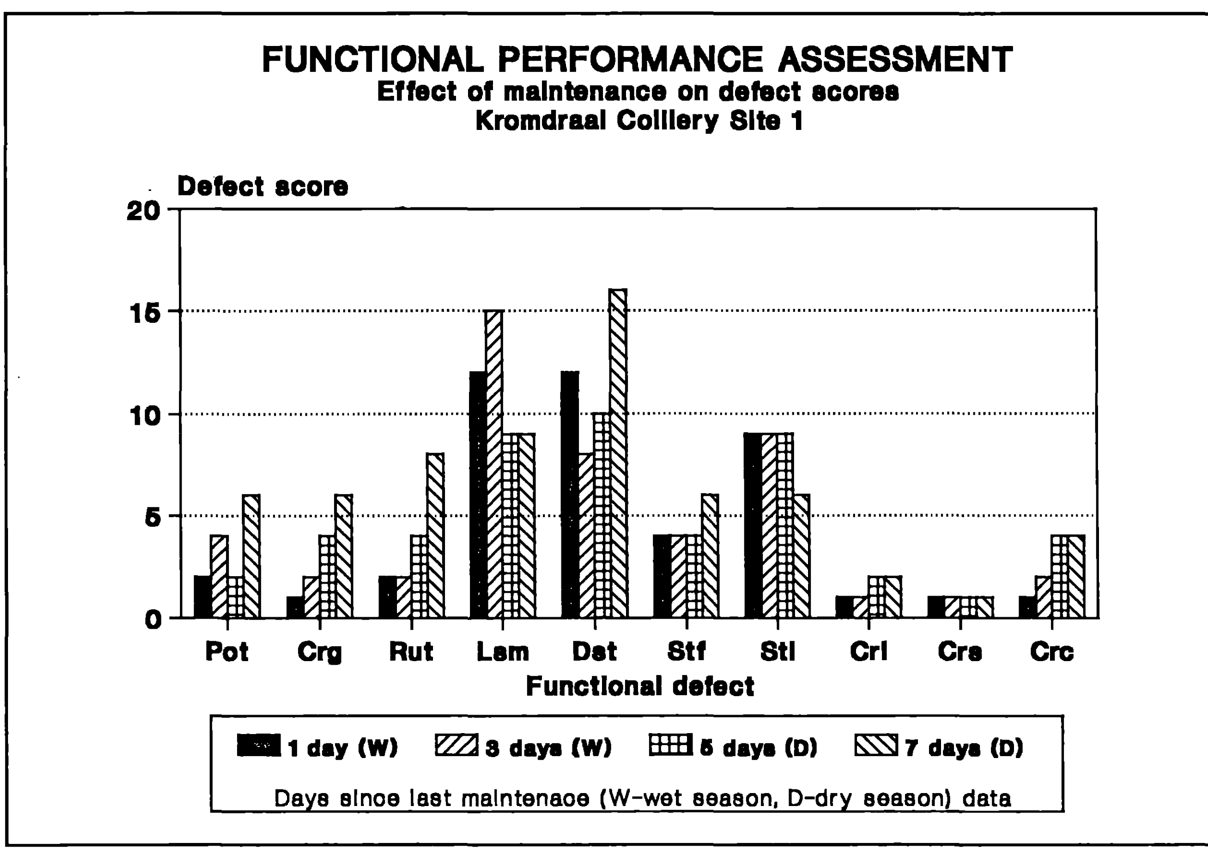


Figure 9.18 Effect of time since last maintenance on defect scores, Kromdraai Colliery site 1.

was noted (along or across the road). In addition, no major differences in functional performance were noted between laden and unladen sides of the road. Figure 9.20 illustrates cracking in the centre of the road due to local failure and movement of the wearing course to a depth of 30-40mm. This may be explained by the braking action of the loaded haulers developing shear forces and tensile forces in the pavement, together with the layering that takes place on the road due to successively blading wearing course off and on the road in wet weather and the formation of a "blad". This type of functional defect may be associated with the high plasticity index (PI) evident from the material classification (Table 3.10) and the gradual reduction in binder material that can be anticipated as the wearing course is repeatedly bladed off the road during the wet season (Paige-Green, 1989). Inadequate scarifying prior to the replacement of the wearing course will lead to the development of layers, especially if coal fines are also present on the road surface. Figure 9.21 shows the typical location of this defect on the right hand track of the laden side of the road, shown in the photograph on the far side of the road.

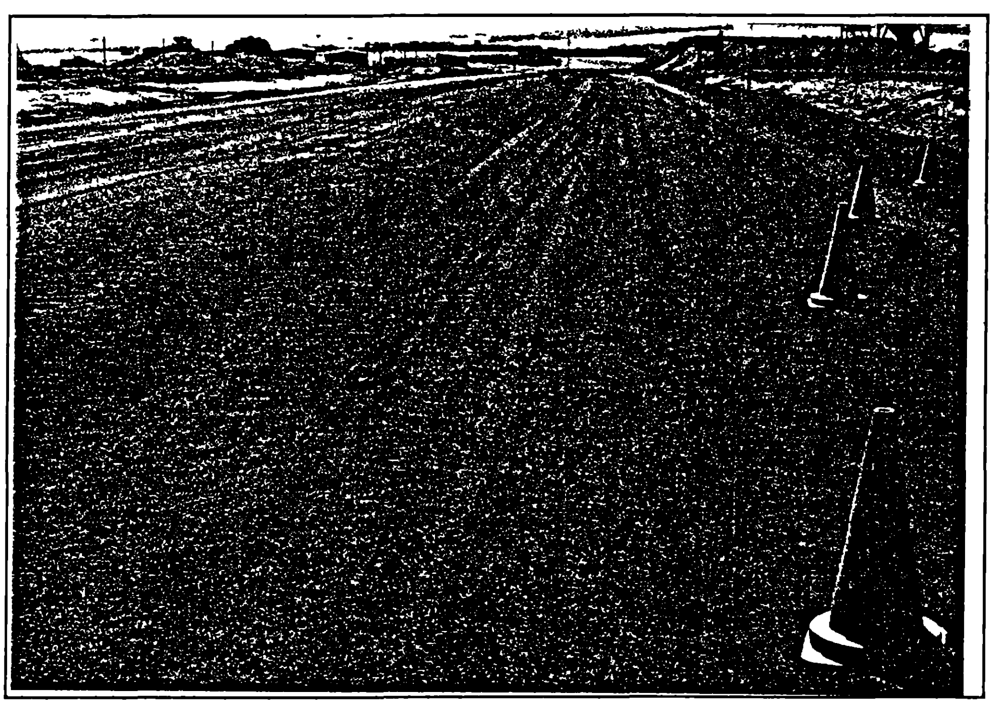


Figure 9.19 General View of SACE Kromdraai Colliery Site 1

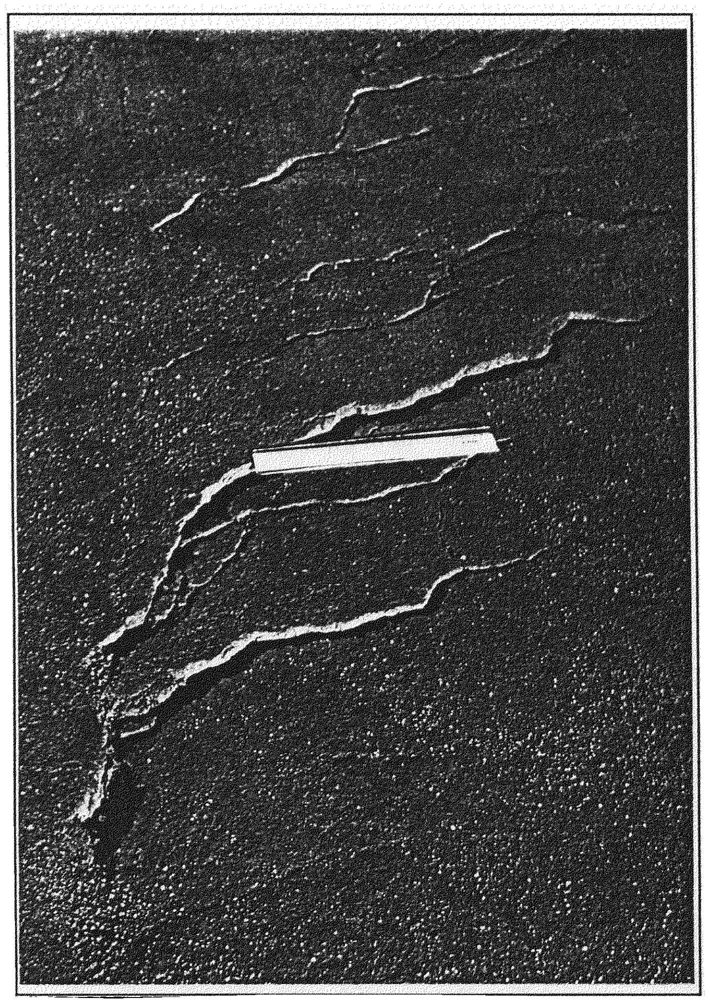


Figure 9.20 Cracking and pushing out of wearing course in centre of road, Kromdraai Colliery Site 1.

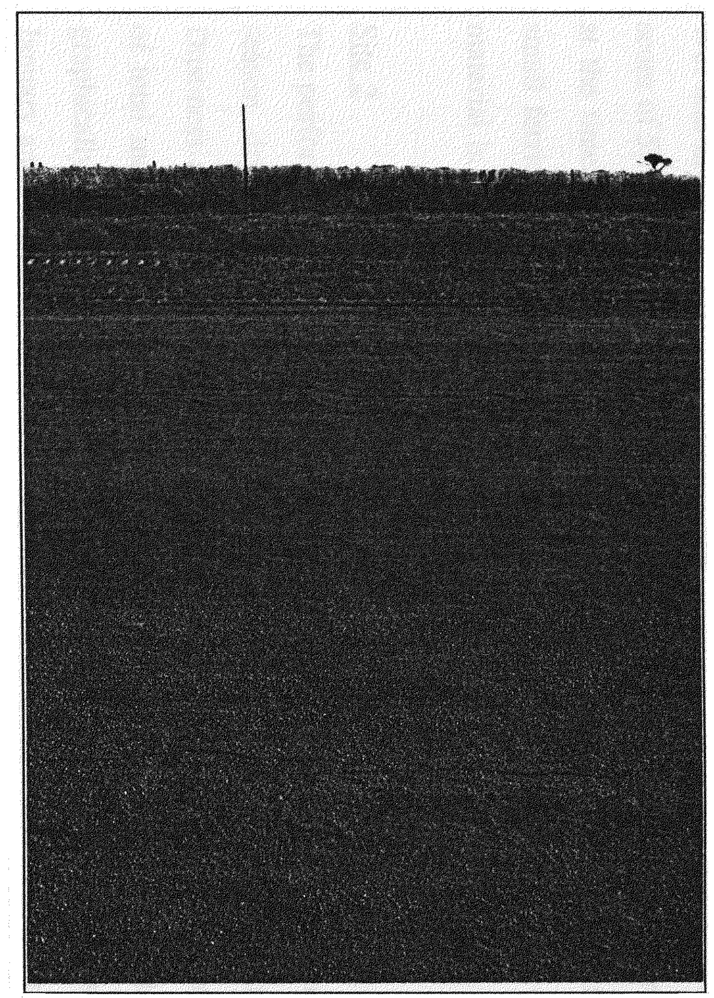


Figure 9.21 View across haul road at Kromdraai Colliery site 1 showing location of defect in centre of road.

Wet and dry skid resistance defect scores averaged 15 and 17 respectively (using an extent score of 5). Wet skid resistance was variable and dependant on the wearing course condition at the time of assessment. Dry skid resistance was adversely affected by the presence of small ferricrete nodules (<2mm diameter), recorded as loose material on the road. This material is evident in Figure 9.19.

Site 2

The performance of site 2 over the assessment period in terms of individual and average wet season, dry season and annual defect scores is presented in tabular form in Appendix F2. Dustiness and loose material were again the major defects reported (approx. 25% and 16% of total material defect score respectively). Figure 9.22 shows the relative defect scores graphically together with the effect of wet weather on dust defect scores for the months of January and February 1995. From Figure 9.16 a similar long term performance trend to site 1 is seen and from Figure 9.17, the effect of maintenance in reducing functional defects is seen together with a slightly lower rate of increase in defect scores after maintenance due to the lower traffic levels on this road. It should be noted that a maintenance interval of 19 days is not normal procedure but arose due to unavailability of the grader for maintenance. Such an interval does provide evidence that without maintenance, the rate of decrease in functionality may decrease over time until some stable terminal condition is reached. This condition will almost certainly be far below the required level of functional performance for the road. In terms of the effect of time between maintenance intervals, a similar trend in defect scores is seen as for site 1 (Figure 9.18).

A general view of Site 2 is shown in Figure 9.23. No differences in functionality were evident between grade and level sections of the road for either laden or unladen sides of the road. There was more damage seen on curved sections of the road on the laden side, due primarily to the shearing action induced by the vehicle tyres and the high PI of the wearing course. Crocodile cracking was noted throughout the dry season (May-September 1994), typical of which is shown in Figure 9.24, each block being approximately 300mm x 300mm. This defect was much reduced in both degree and extent over the wet season, this again being indicative of a material with a high PI value. Figure 9.25 illustrates the combined effect of a valley in the road longitudinal profile coincident with an excessive crossfall. The

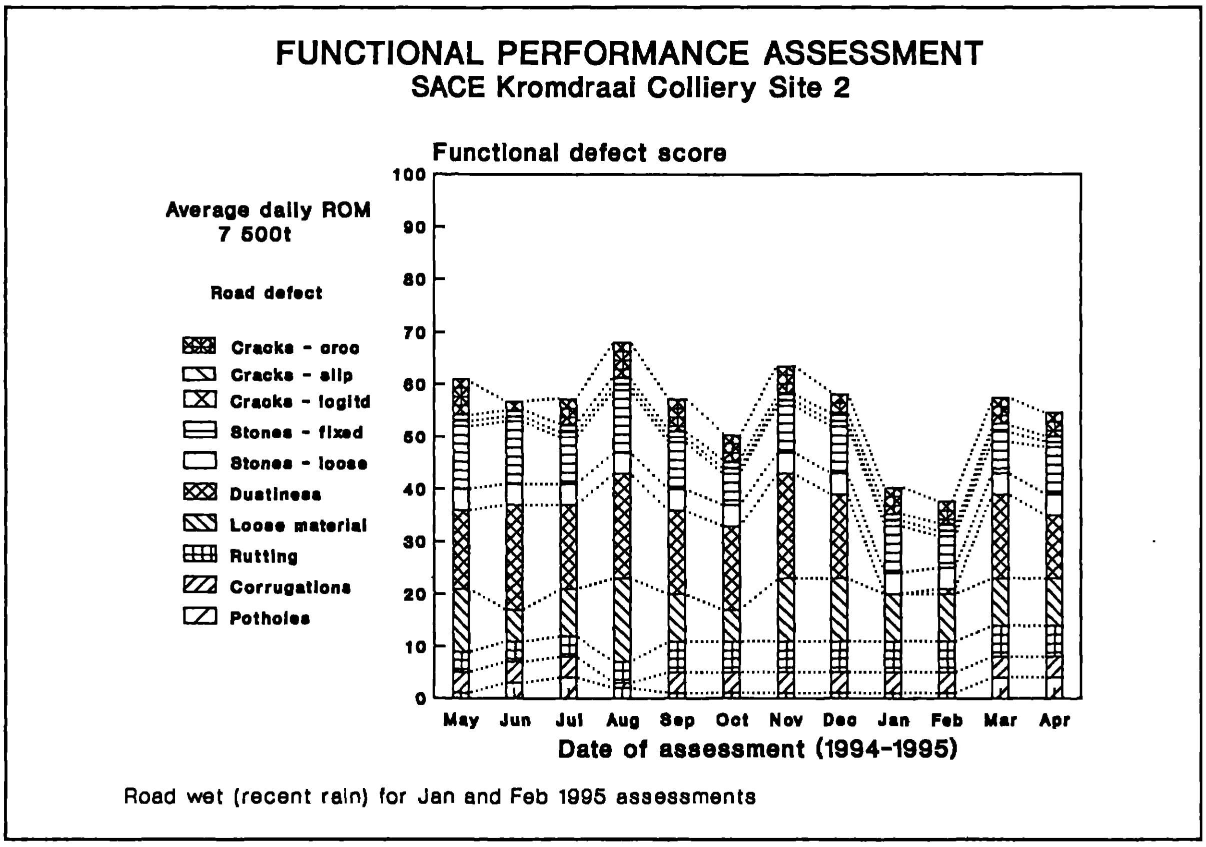


Figure 9.22 Functional Performance Assessment - SACE Kromdraai Colliery site 2

Figure 9.23 General View of SACE Kromdraai Site 2 (laden side of road on LHS).

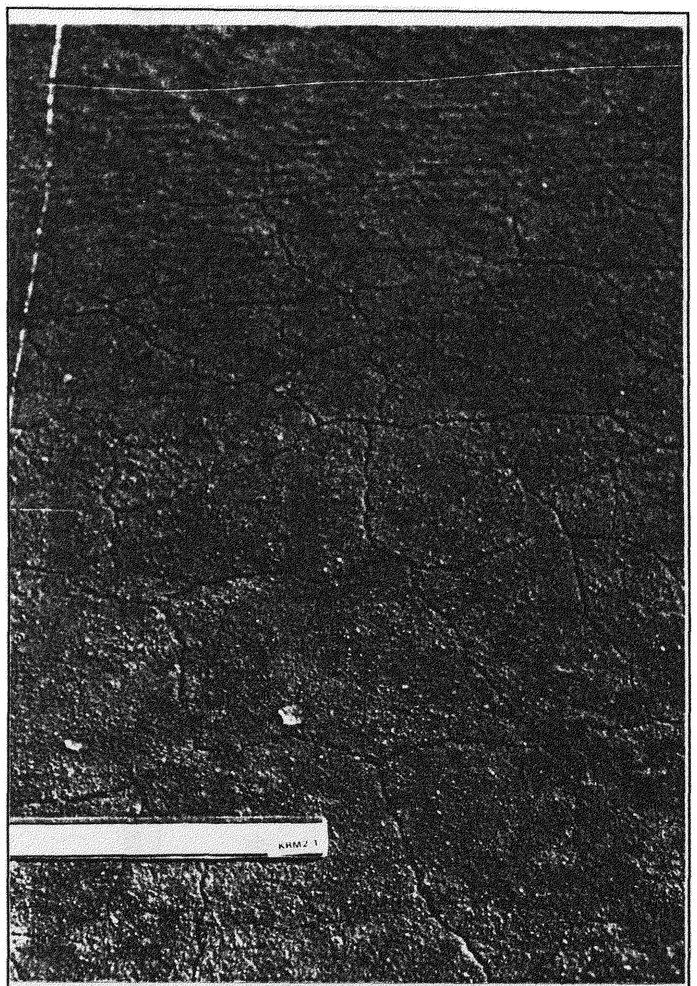


Figure 9.24 Typical crocodile cracking defect at SACE Kromdraai Colliery site 2.

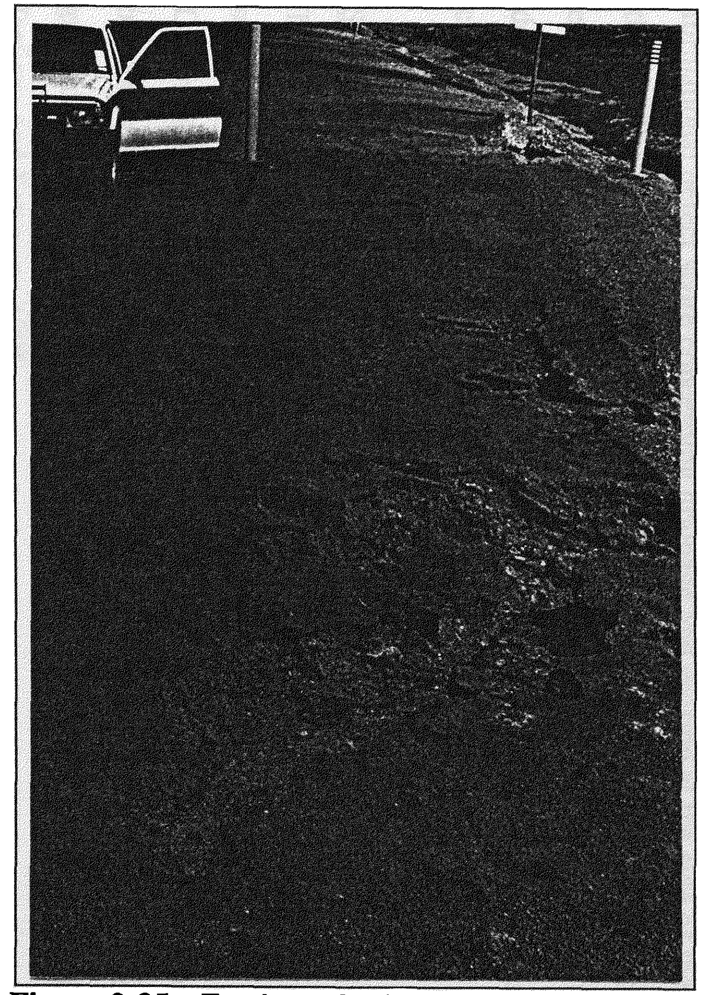


Figure 9.25 Erosion of edge of road coincident with road valley and locally excessive crossfall, SACE Kromdraai Colliery site 2.

formational defect score concerning drainage and erosion at the side of the road was high in this localised area due to the above mentioned effects, when combined with rain, leading to excessive runoff stream velocities and resultant scouring of the road. Corrugation type defects developed in the road as a result of the scouring if maintenance was not immediately carried out.

Site 3

The performance of site 3 over the assessment period in terms of individual and average wet season, dry season and annual defect scores is presented in tabular form in Appendix F2. Dustiness and loose material were again the major defects reported (approx. 22% and 24% of total material defect score respectively). Figure 9.26 shows the relative defect scores graphically together with the effect of wet weather on dust defect scores for the months of January and February 1995.

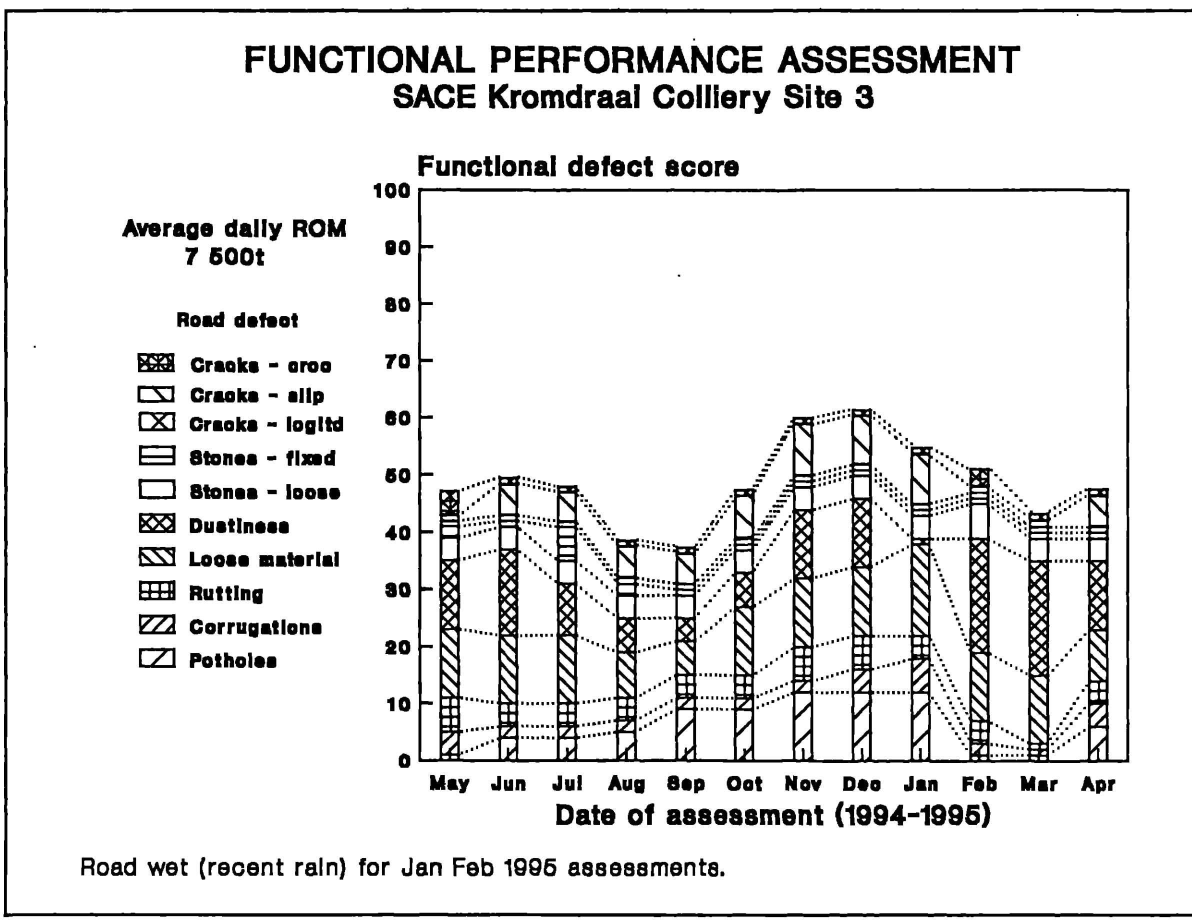


Figure 9.26 Functional Performance Assessment, SACE Kromdraai Mine site 3.

From Figure 9.16 the long term performance trend shows decreasing functional defect scores as traffic steadily increases over the dry season, but as rainfall and traffic levels increase to an average of 7 500t per day, functional defect scores are seen to increase. Of the three sites assessed at Kromdraai Colliery, this site is the most sensitive to rainfall, due to a combination of recent construction and light traffic volumes. Figure 9.17 shows the effect of maintenance in reducing functional defects and a lower rate of increase in defect scores after maintenance due both to the lower traffic volume on this road and the superior CBR strength values for this particular ferricrete. After maintenance, defect scores reduce over a period of ten days whence they begin to increase. Referring to Figure 9.27 it is seen that the defects of loose material, dust and potholes (and their associated slip cracks) contribute most to this effect. The dust defect at this site was particularly high and can be associated with the low PI and LL of the material and an overall lack of binder material.

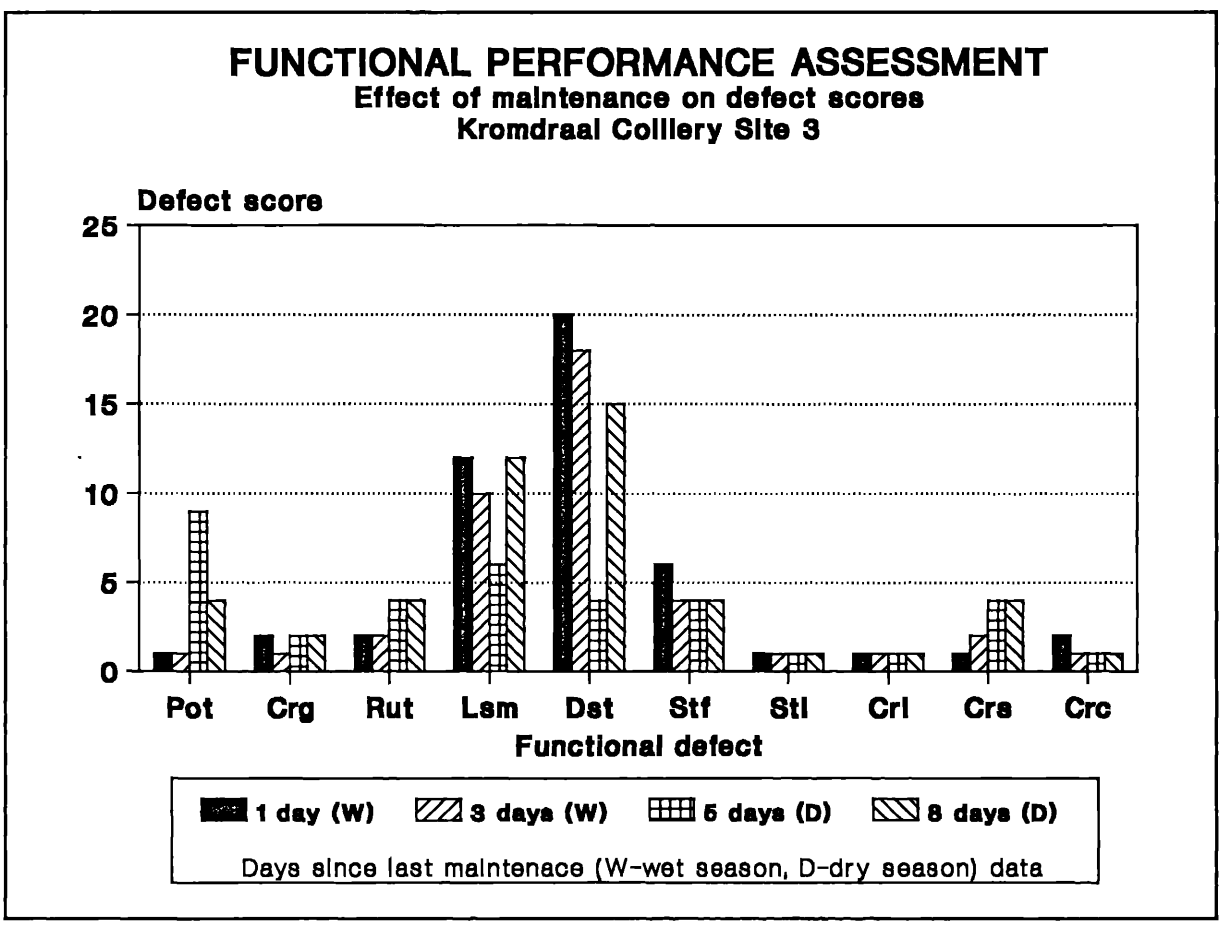


Figure 9.27 Effect of time since last maintenance on defect scores, Kromdraai Colliery site 3.

Since the road is relatively new and traffic has increased steadily from Feb 1994 onwards, some local deformation may be expected. This is seen in Figure 9.28 where slip cracks at the side of the road and potholes in the centre of the road are seen. The pothole defect appears to increase with the increasing cumulative traffic up to November 1994 from whence it remains constant, eventually being reduced by blading after rain in January. No further excessive pothole defect scores were recorded after this initial compaction of soft spots in the road. Both effects were noted on both laden and unladen sides of the road with only a slight increase in shearing damage seen on road bends.

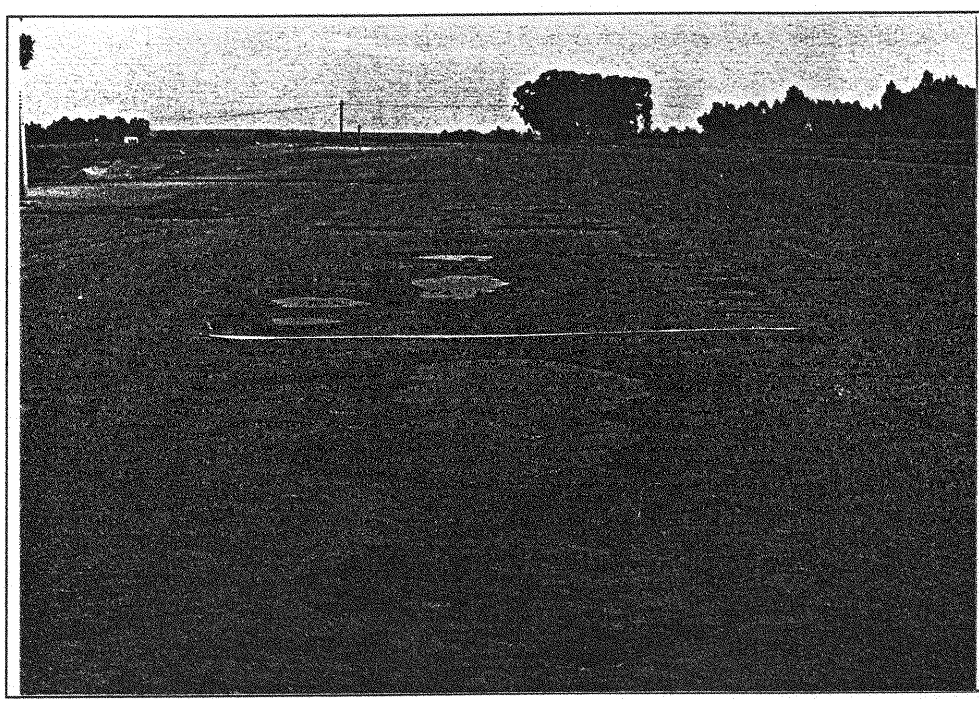


Figure 9.28 Potholing as a result of localised soft spot in newly constructed and trafficked site 3 road at SACE Kromdraai Colliery.

Wet weather trafficability of the road was poor immediately after a period of rain, as seen in Figure 9.29. Churning of the wearing course occurs to a depth of 30-50mm. Wearing course material below this depth remains firm when only isolated heavy showers occur. Should more continuous rain fall, excessive churning occurs under the action of the haul trucks. In these conditions, coal haulage is temporarily suspended and the damaged wearing course is bladed off the road until dry. With the return of this material to the road, no evidence of layering was seen. This may be ascribed to several factors; the lack of coal contamination of the wearing course material, the age of the road and the lack of a "blad".

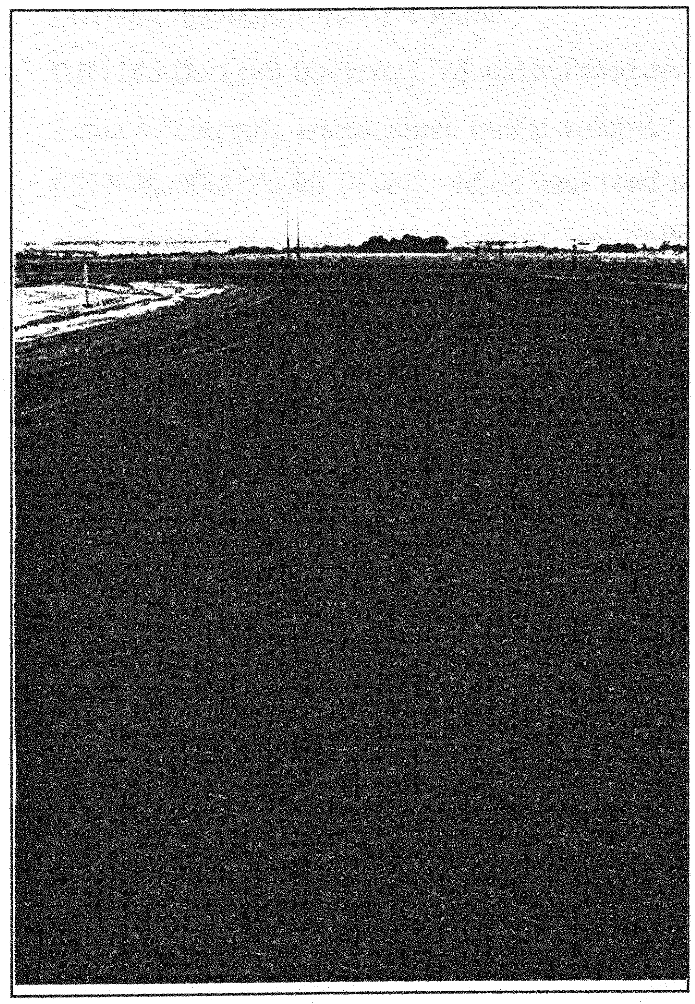


Figure 9.29 Churning of wearing course after recent rain, Kromdraai Colliery site 3 (laden side of road LHS)

It may be anticipated that as fine coal spillage and the age of the road increases, the differences in the on- and off-road material (loss of binder) may induce layering in the dry season as seen at the other sites.

9.3.3 Results of Performance Monitoring - New Vaal Colliery

In the experimental design outlined in Chapter 3.3.2.3, three test sites were identified at New Vaal Colliery. Their location is given in Figure 3.10 and summarised below.

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.

The wearing course material is not sourced on the mine, being a mixture of dolerite (crusher run scalpings), soft plinthite and ash in the ratio 40%, 40% and 20%. The wearing course material is classified as a G7 material (following CSRA TRH14, 1985) for all mine sites. The materials are accordingly similar, only differing in the range of 95%-100%Mod AASHTO CBR values, the weaker material being found at sites 2 and 3 which are more recent constructions than the original haul road (site 1).

Traffic volumes encountered remained approximately constant for sites 1 and 2, at 50 000t and 26 000t per day respectively, whilst site 3 showed more varied traffic volumes of between 3 500t and 16 500t per day over the analysis period. Despite these variations, this combination of circumstances enables the functional performance of the roads to be assessed under various traffic volumes. The performance of each site is summarised in the sections that follow.

Site 1

The performance of site 1 over the assessment period in terms of individual and average wet season, dry season and annual defect scores is presented in tabular form in Appendix F3. Dustiness, loose material and crocodile cracking defects contributed the most to the total material defect score of 60 by approx. 20%, 15% and 12% respectively. These defect scores are shown graphically in Figure 9.30 from which it is seen that although individual defect scores vary slightly, there is no obvious trend.

The long term functional performance of site 1 is shown in relation to the remaining sites at New Vaal Colliery and the seasonal rainfall in Figure 9.31 from which it is seen that the defect scores recorded at site 1 increase with the onset of rain, eventually returning to

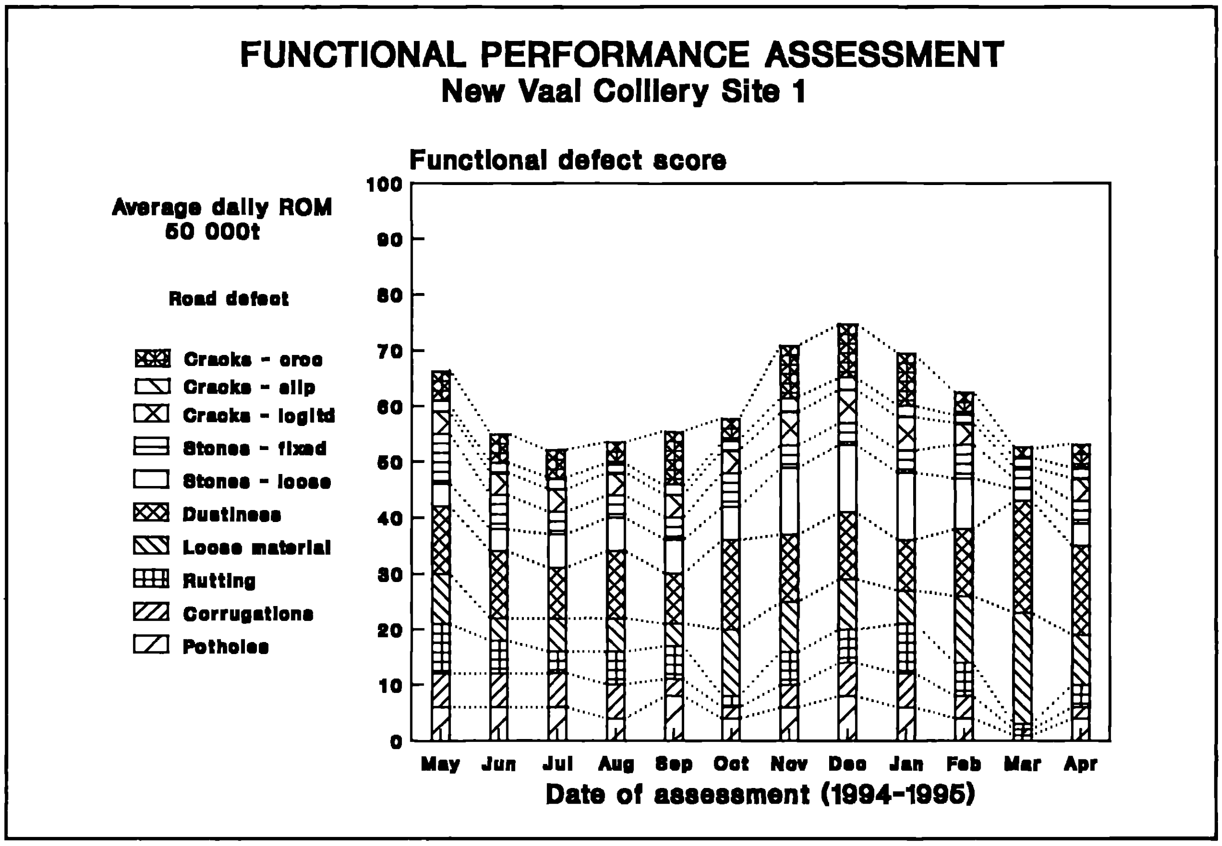


Figure 9.30 Functional Performance Assessment, New Vaal Colliery Site 1.

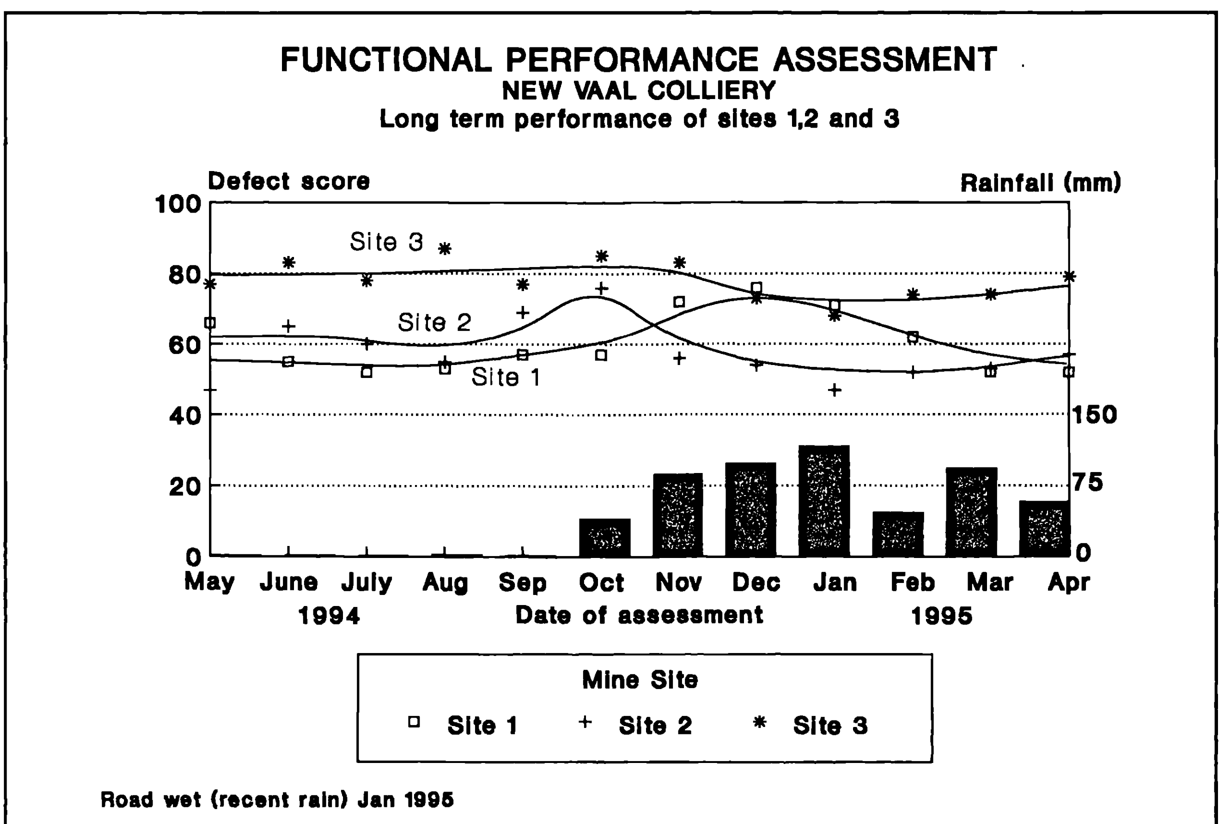


Figure 9.31 Long Term Performance Assessment of Sites 1, 2 and 3, New Vaal Colliery

approximately similar values at the end of summer as recorded in the winter. If the variable of days since last maintenance is included in the analysis of defect score, a trend becomes obvious as shown in Figure 9.32. There is a decrease in defect scores immediately after maintenance takes place on the road due to a decrease in dust, loose material and loose stoniness defects scores as a result of blading, for between 2 and 3 days. Then follows a period of steadily increasing defect scores. Figure 9.33 illustrates the response of defect scores after maintenance over a period of one to eight days for site 1.

The relationship with traffic levels (tons/day) is also obvious when sites 1 and 2 are assessed in terms of the rate of decrease of functionality with traffic volume. Site 3 does not follow the anticipated trend due to the low levels of maintenance applied to this section of lightly trafficked road. This implies that the level of functional performance expected from a particular wearing course material can be related to the traffic volumes it carries.

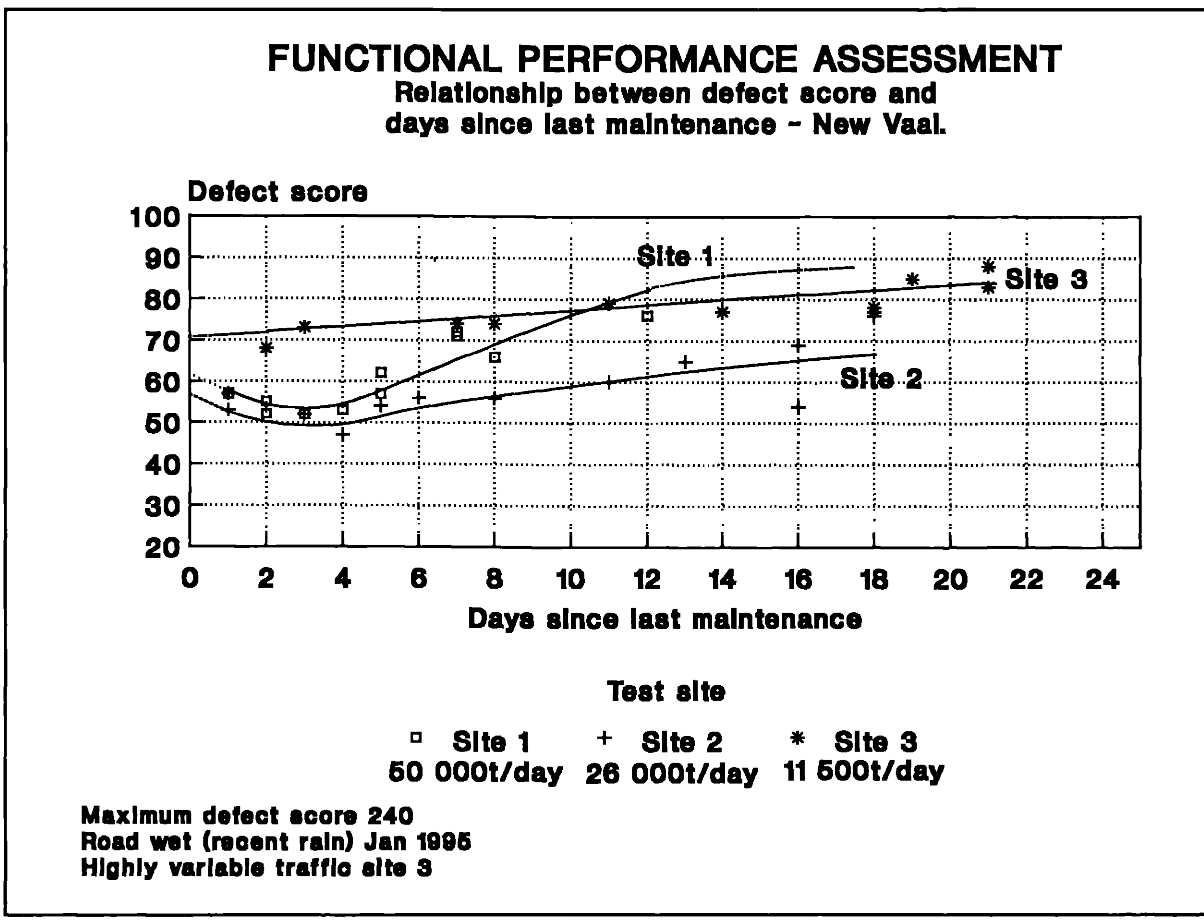


Figure 9.32 Effect of Maintenance on Defect Score - New Vaal Colliery Sites 1, 2 and 3.

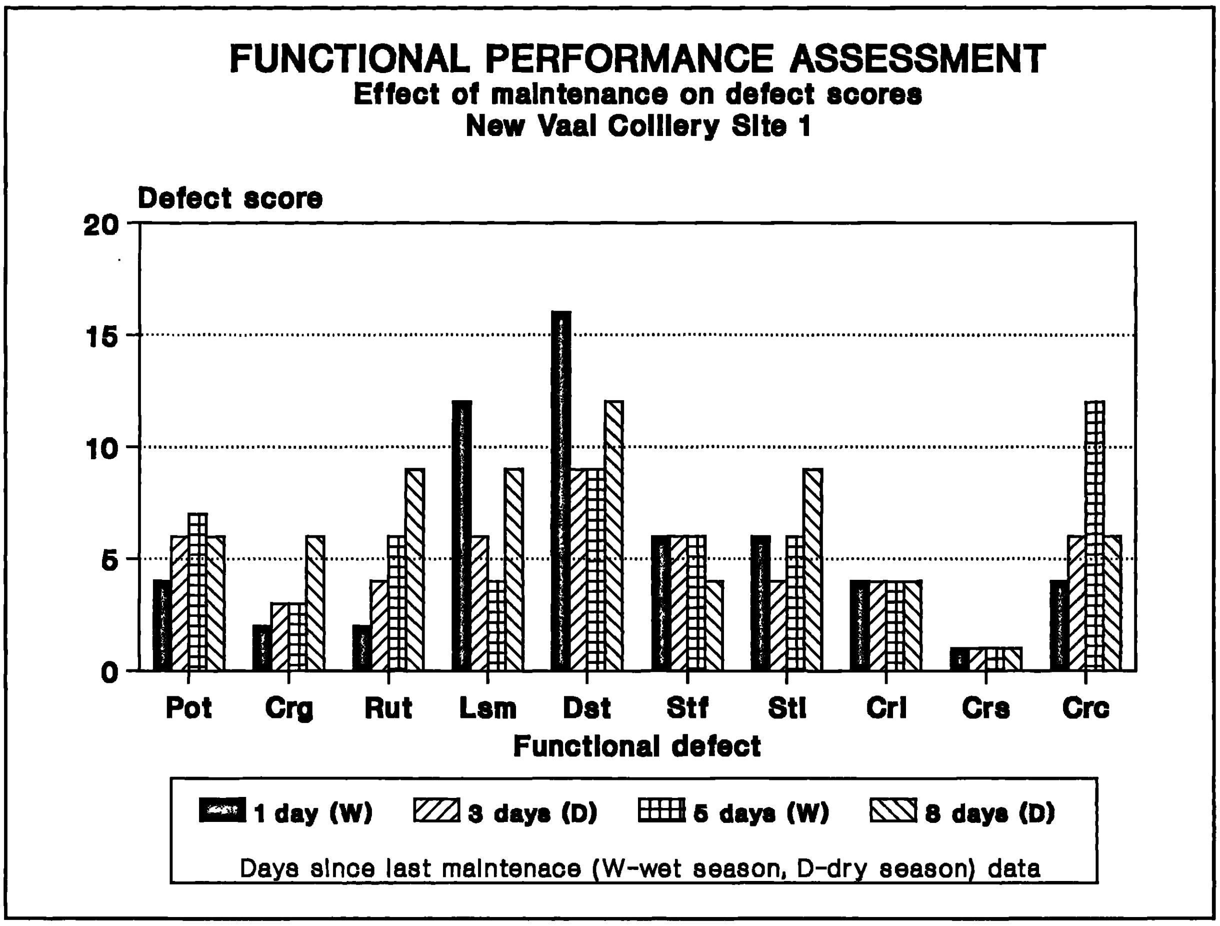


Figure 9.33 Effect of time since last maintenance on defect scores, New Vaal Colliery site 1.

Site 1 dust conditions are illustrated in Figure 9.34 during the dry season, with no water or dust palliative recently applied. For comparative purposes, Figure 9.35 shows the same section of road following recent rain. The wearing course is seen to churn to a depth of approximately 25mm during wet weather. This material is bladed off the road until dry and returned during the next maintenance cycle. As opposed to the other mine sites investigated, no layering was evident when this material was returned. The onset of potholing was seen to be associated with the small scale "pock-marks" of 30-40mm diameter, 10-20mm deep as illustrated in Figure 9.36 (road surface moist). Figure 9.37 shows the further development of potholes under the action of the haul trucks. This may be indicative of a steady reduction in the amount of binder material in the wearing course as seen from reference to the PI and LL values in Table 3.11, due possibly to successive blading of the material.

Site 1 only offers horizontal sections of road and there is no clear distinction between laden

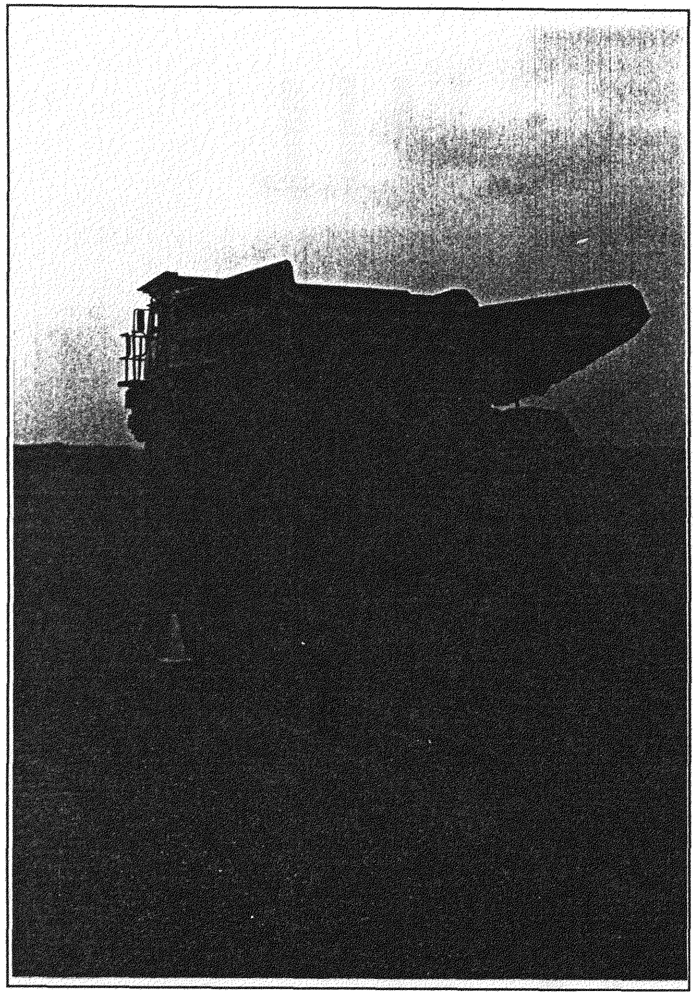


Figure 9.34 Haul Road Dust Defect (Dry Road), New Vaal Colliery Site 1

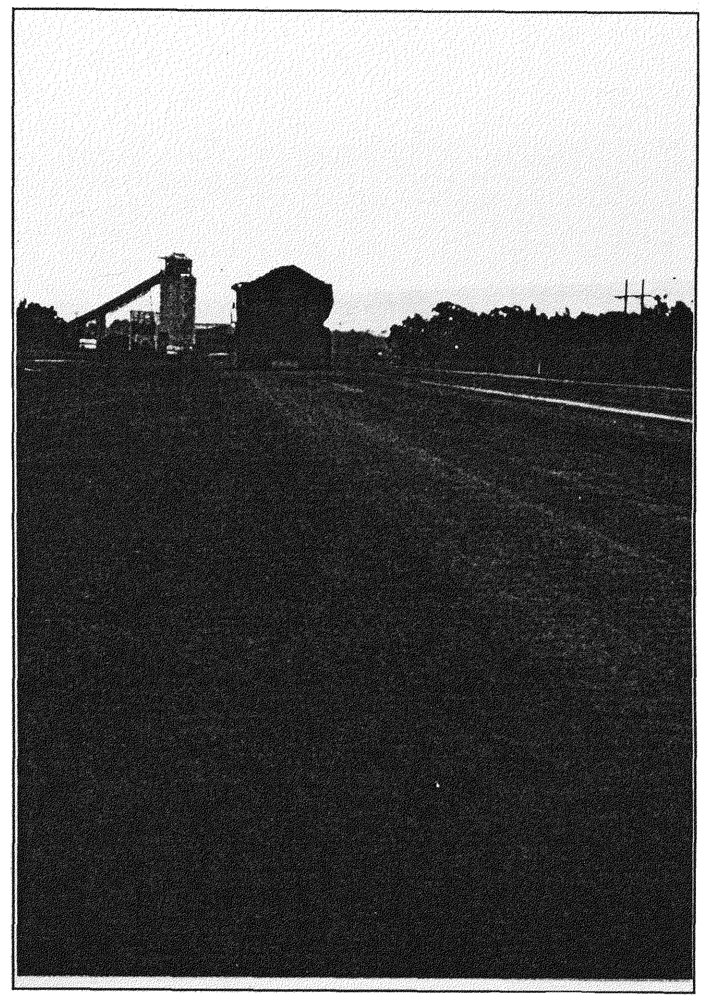


Figure 9.35 Dust Defect Conditions (wet road), New Vaal Colliery Site 1

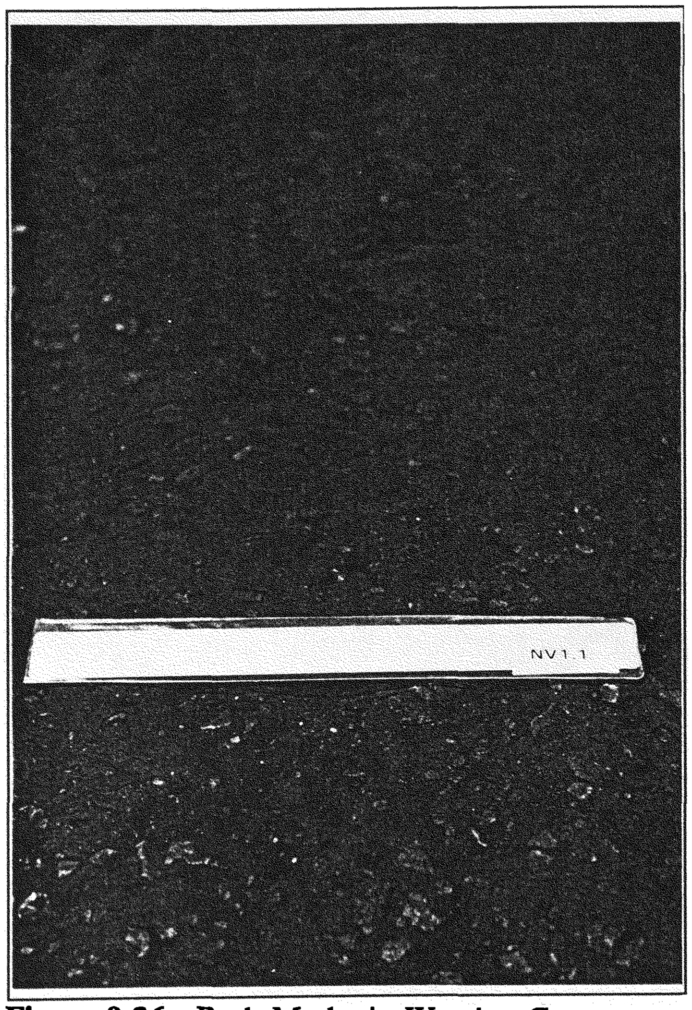


Figure 9.36 Pock Marks in Wearing Course as a Precursor to Larger Potholing (Figure 9.37), New Vaal Colliery Site 1.

and unladen sides of the road due to the return of discard material to the pit. Discards amount to approx. 40 laden truck repetitions per day (or 12% of the unladen repetitions). Wet and dry average skid resistance defect scores of 14 and 13 (using an extent score of 5) were confirmed by observation as being associated with heavy rains (refer to Figure 9.35, note lack of churning, possible related to higher CBR values at this site) and for dry conditions, excessive loose material (associated with blading). There were no major differences in functionality recorded between either side of the road.

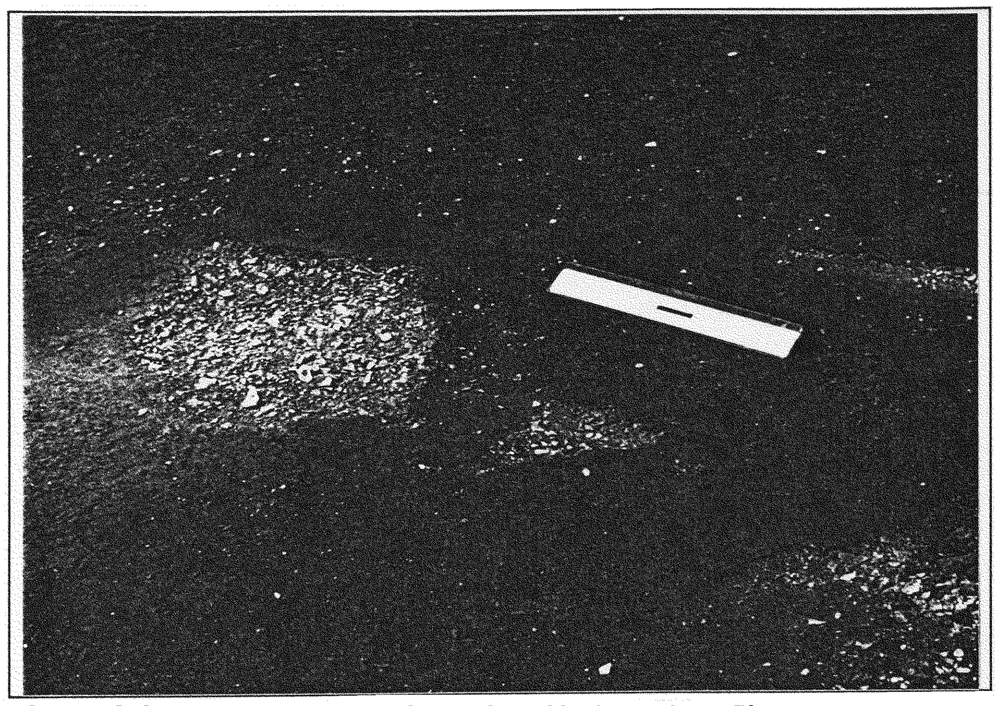


Figure 9.37 Pothole Formation, New Vaal Colliery Site 1.

Site 2

The performance of site 2 over the assessment period in terms of individual and average wet season, dry season and annual defect scores is presented in tabular form in Appendix F3. Dustiness, loose material, fixed stoniness and loose stoniness defects contributed the most to the total material defect score of 57 by approx. 23%, 14%, 14% and 12% respectively. These defect scores are shown graphically in Figure 9.38 from which it is seen that although individual defect scores vary slightly, there is no obvious trend. The much reduced dust defect rating for January 1995 is attributed to the wet condition of the road.

Figure 9.32 illustrates the effect of maintenance interval on defect scores for site 2, from which it is seen that site 1 and 2 exhibit a similar performance, site 2 showing a reduced rate of increase in defect scores which may be associated with the reduced traffic volume the road handles compared with site 1.

The wet skid resistance of the road receives a high defect score due to polishing of the wearing course which becomes apparent on the laden side of the road during dry periods. Any subsequent rain causes short lived problems with wet skid resistance, until the road

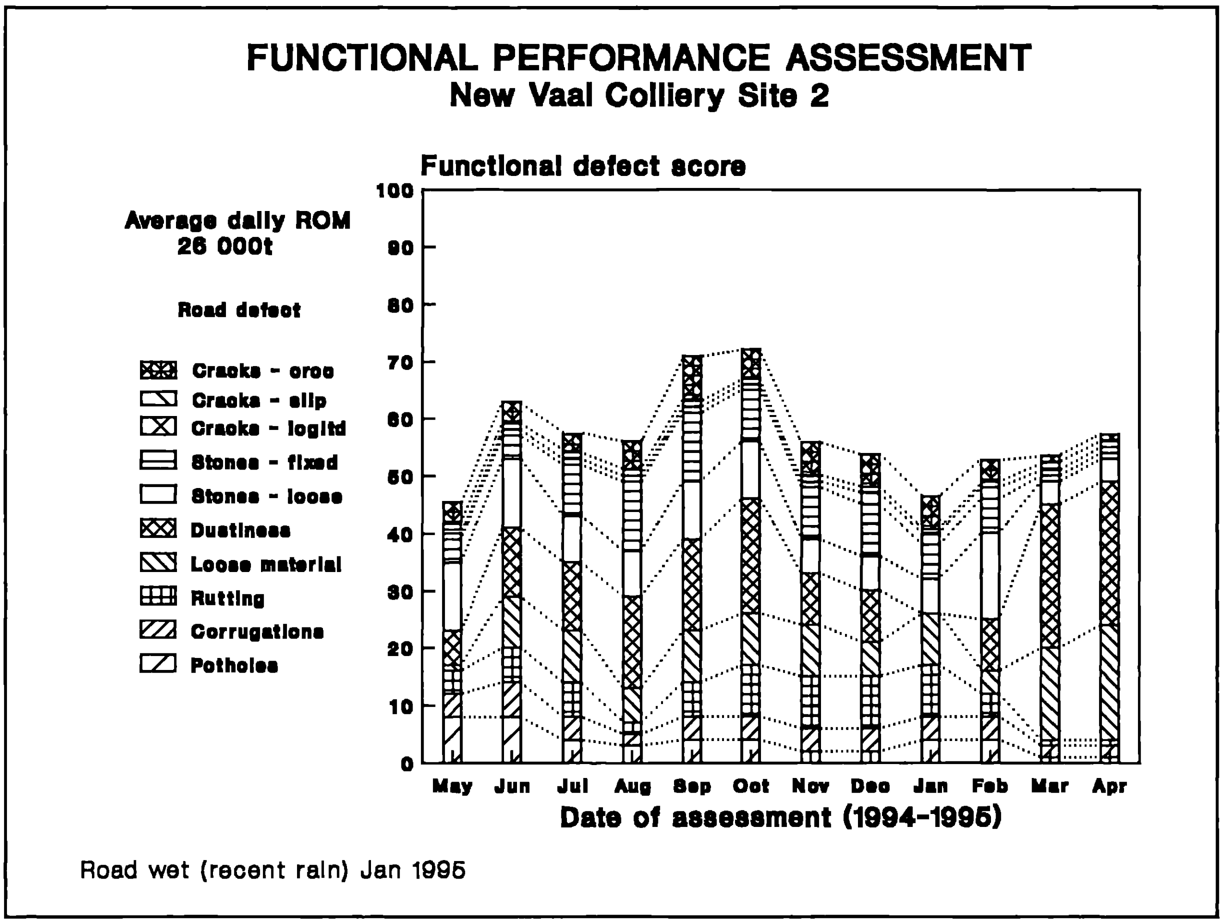


Figure 9.38 Functional Performance Assessment, New Vaal Colliery Site 2.

begins to cut up. Associated with this effect may be the excessive crossfall at points along the test section; the resultant crabbing action of the truck contributing to the polishing phenomenon. Stoniness was also a significant defect on the road, both fixed and loose stones. This is due to oversize material in the wearing course material as shown in Figure 9.39. The problem is particularly critical on bends in the road where the shearing action of the haulers damages the road leaving large stones exposed to damage vehicle tyres as shown in Figure 9.40. Figure 9.41 illustrates localised slip cracking and rutting as a result of sub-base compaction and/or shear failure.

Site 3

The performance of site 3 over the assessment period in terms of individual and average wet season, dry season and annual defect scores is presented in tabular form in Appendix F3. Dustiness, loose material and fixed stoniness defects contributed the most to the total material defect score of 78 by approx. 23%, 19% and 15% respectively. These defect scores are

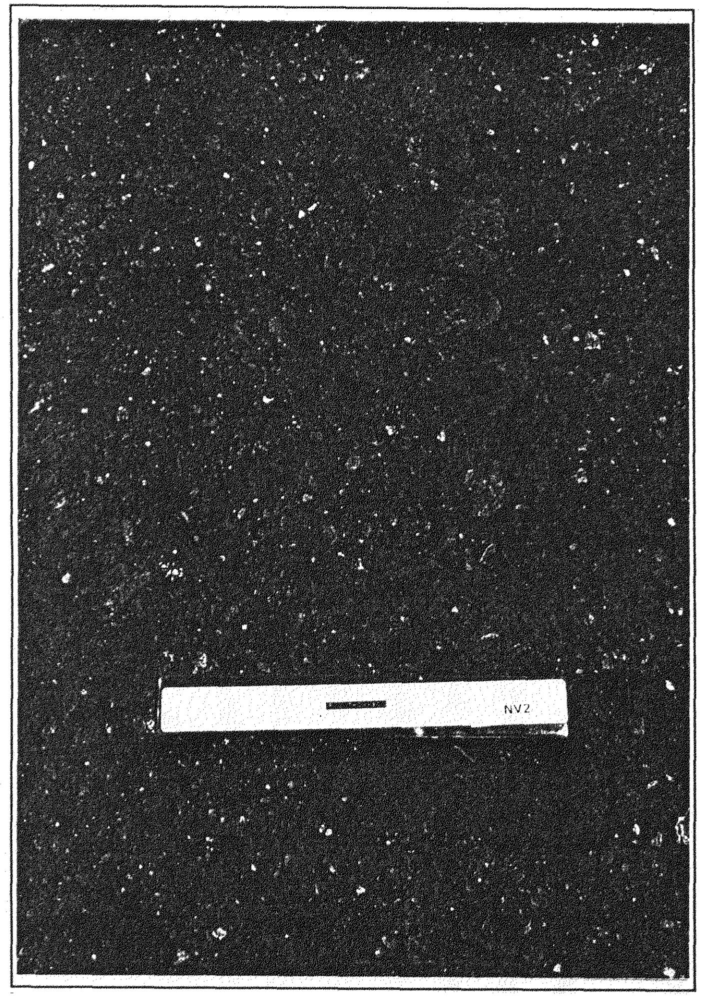


Figure 9.39 Stones fixed in wearing course, New Vaal Colliery site 2

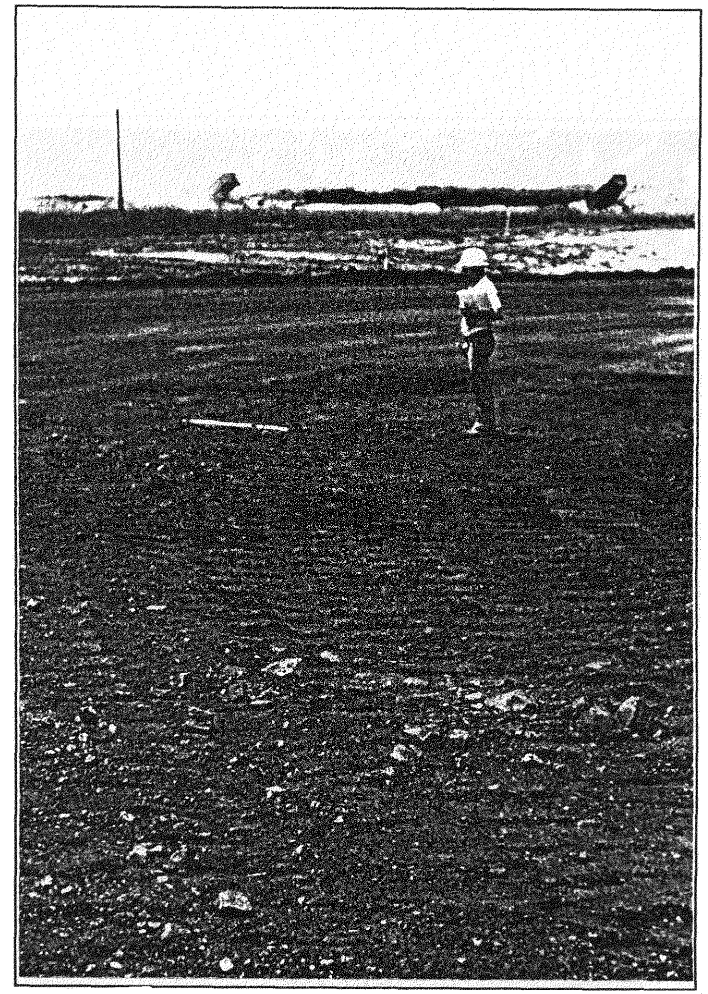


Figure 9.40 Typical damage to wearing course on bends, showing exposed stones, New Vaal Colliery Site 2.

Figure 9.41 Slip cracks and deformation of sub-base, New Vaal Site 2.

shown graphically in Figure 9.42 from which it is seen that although individual defect scores vary slightly, there is no obvious trend. Whilst other defect scores remain comparable to sites 1 and 2 the larger total defect score is mainly attributable to the dust and loose material defect scores. Figure 9.32 reveals that a much higher maintenance interval is applied at this site, primarily due to the lower traffic volumes handled by the road. If traffic volumes and defect scores are considered across all sites it would appear that a threshold traffic volume is implicated. Assuming similar wearing course materials, above this threshold traffic volume the increase in road defects is proportional to the increase in traffic. Below this threshold traffic volume, road defect scores and traffic volume do not correlate as is shown in Figure 9.32. Figure 9.43 illustrates the variation of defect with days between maintenance and although limited to a maximum seven day period (for comparative purposes) over the longer term a steady increase in pothole, corrugation, rutting and fixed stoniness is seen. Dust and loose material defects do not initially decrease after maintenance as with other sites. Blading does not generate much improvement in functionality due in most part to the large stones in the mixture (refer to Table 3.11) which prevent a clean cut being taken and generate loose material and an associated dust defect.

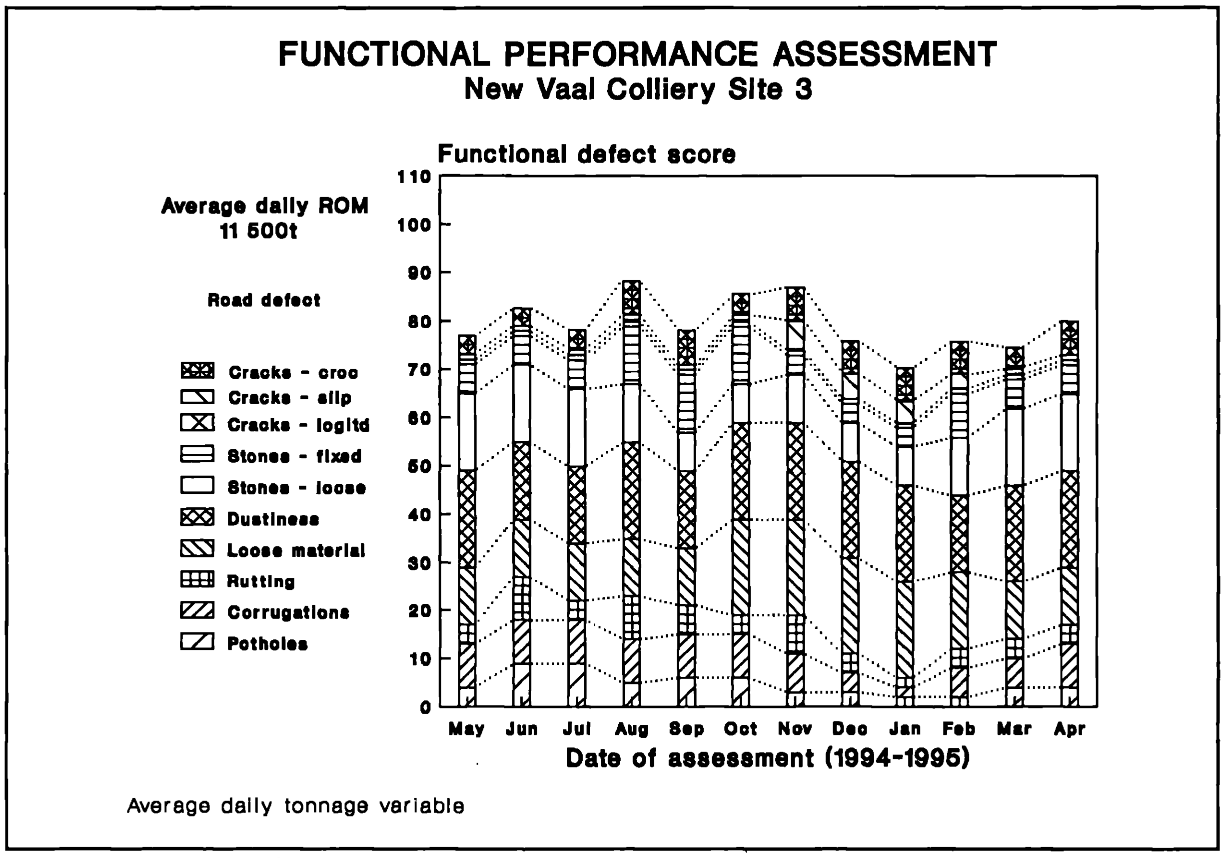


Figure 9.42 Functional Performance Assessment, New Vaal Colliery Site 3.

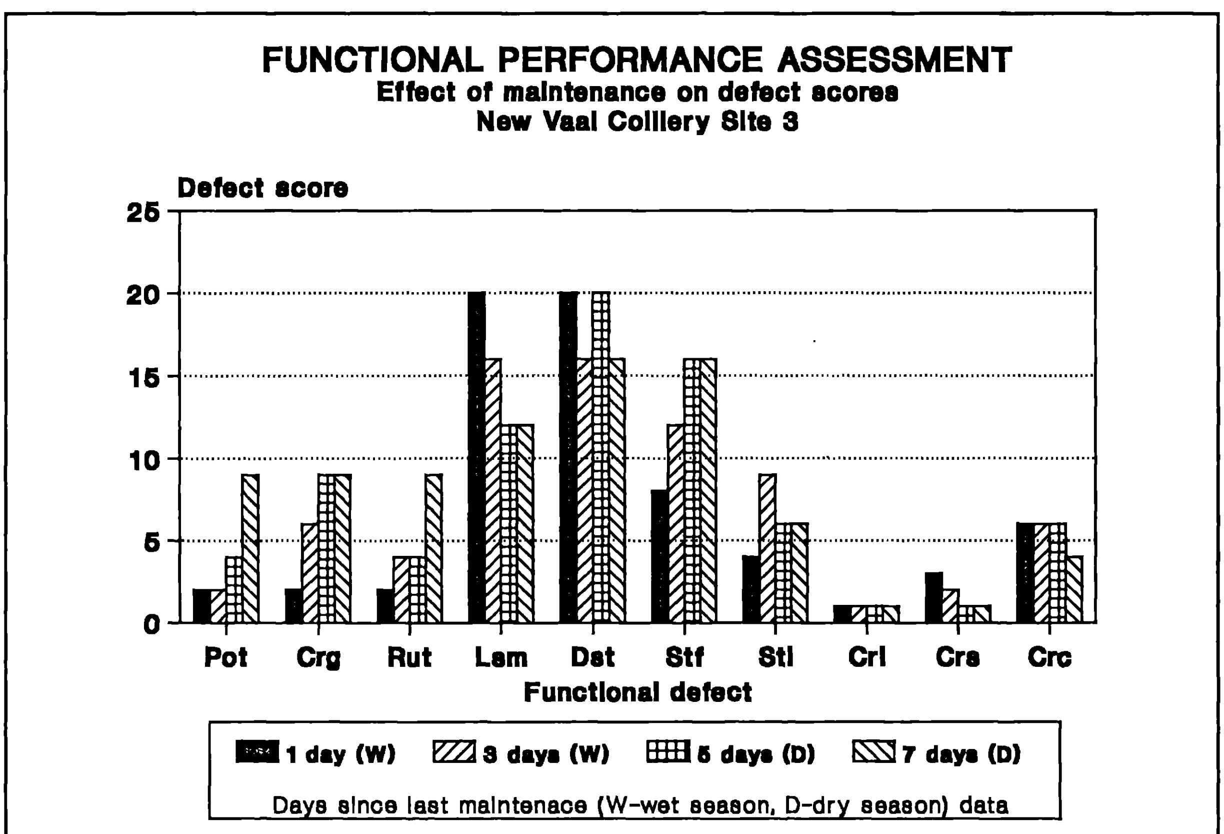


Figure 9.43 Effect of time since last maintenance on defect scores, New Vaal Colliery site 3.

Figure 9.44 shows a general view of site 3 together with the amount of loose material on the road whilst Figure 9.45 the dust defect associated with site 3 under dry conditions without dust watering or palliatives. It is anticipated that under the action of increased traffic volumes and the associated increase in the frequency of maintenance and watering, the functional performance of the site will revert to the more typical performance of site 2, the implication being that a recently constucted haul road is subject to a "running-in" period in which the wearing course material is compacted and functionality increases under the action of traffic, blading and watering.

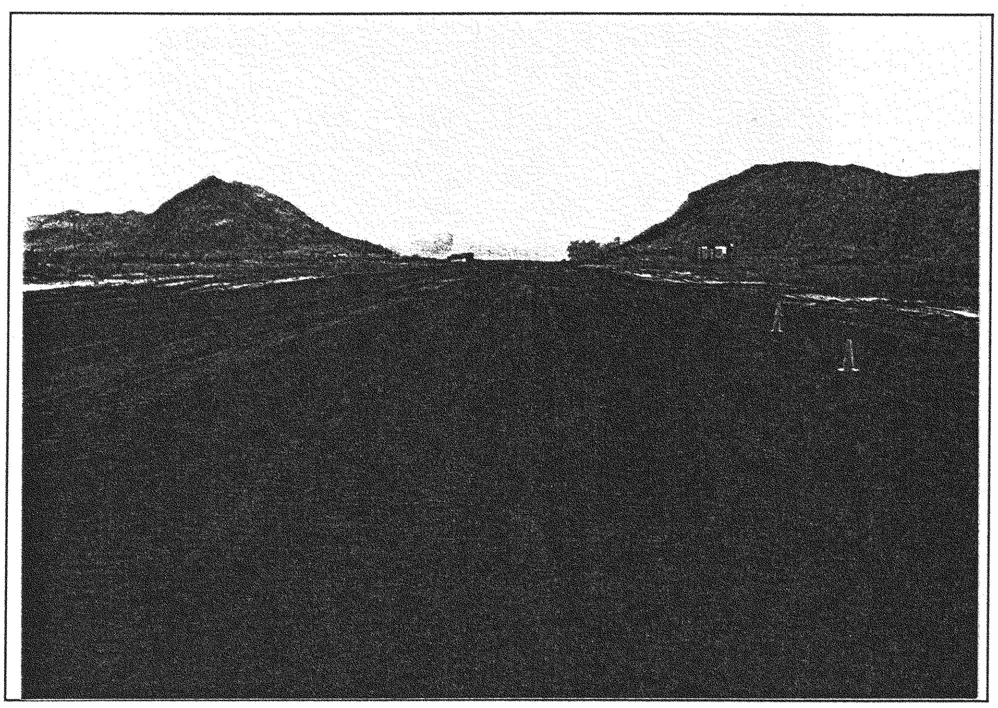


Figure 9.44 General view of New Vaal Colliery Site 3.

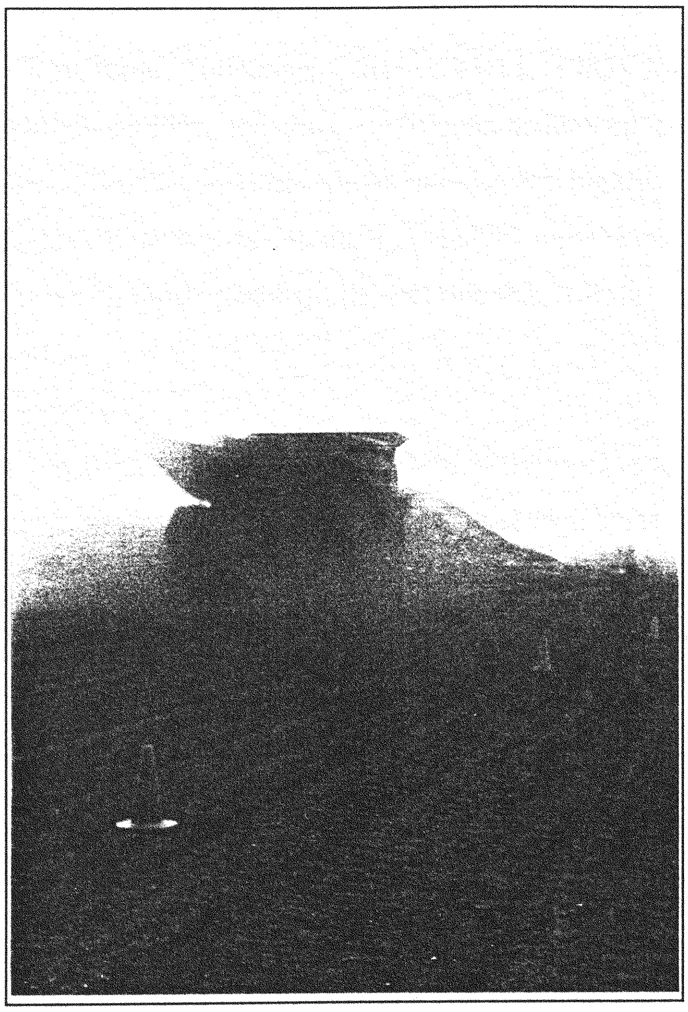


Figure 9.45 Dust defect (dry road) at New Vaal Colliery Site 3.

9.3.4 Results of Performance Monitoring - Kleinkopje Colliery

In the experimental design outlined in Chapter 3.3.2.4, three test sites were identified at Kleinkopje Colliery. Their location is given in Figure 3.11 and summarised below.

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)

The wearing course material is ferricrete, sourced on the mine. The wearing course material is classified as a G7 material (following CSRA TRH14, 1985) for sites 1 and 2. The materials are accordingly similar, the only significant difference being in the 100%Mod AASHTO CBR values. Traffic volumes encountered were highly variable for both sites, between 11 and 143 repetitions per day at site 1, 3 and 87 repetitions per day at site 2. The performance of each site is summarised in the sections that follow.

Site 1

The performance of site 1 over the assessment period in terms of individual and average wet season, dry season and annual defect scores is presented in tabular form in Appendix F4. Dustiness, loose material, fixed stoniness and loose stoniness defects contributed the most to the total material defect score of 72 by approx. 25%, 15%, 15% and 11% respectively. These defect scores are shown graphically in Figure 9.46 from which it is seen that although individual defect scores vary slightly, there is no obvious trend (excepting January 1995 assessment which shows a reduction in dust defect scores due to recent rain). An increase in pothole, corrugation and rutting defect scores were observed over the wet season (Sept 1994-Apr 1995), the remaining defect scores being reduced over the same period. This may be anticipated as the action of increased moisture in the wearing course material will lead to a reduction in strength which can be related to most of the above defects. The increase in corrugation defect does not appear to correlate with the expected material behaviour over the wet season, since it may be expected that corrugations are flattened by vehicles in the wet season. A possible explanation may either be compaction of moist loose material under particularly low traffic volumes, or as a result of blading, either due to troughs only being loosely filled with material (this material is subsequently removed by whip-off or erosion to recreate the corrugations), or due to the effect of large protruding stones artificially creating isolated corrugations.

The long term functional performance of site 1 is shown in relation to site 2 at Kleinkopje Colliery and the seasonal rainfall in Figure 9.47 from which it seen that whilst site 2 appears to be sensitive to rainfall (in terms of an increase in defect scores) no such effect is seen for site 1. This effect may be obscured by the variation in traffic levels over the period. The defect scores of both sites, although variable from month to month, follow approximately the

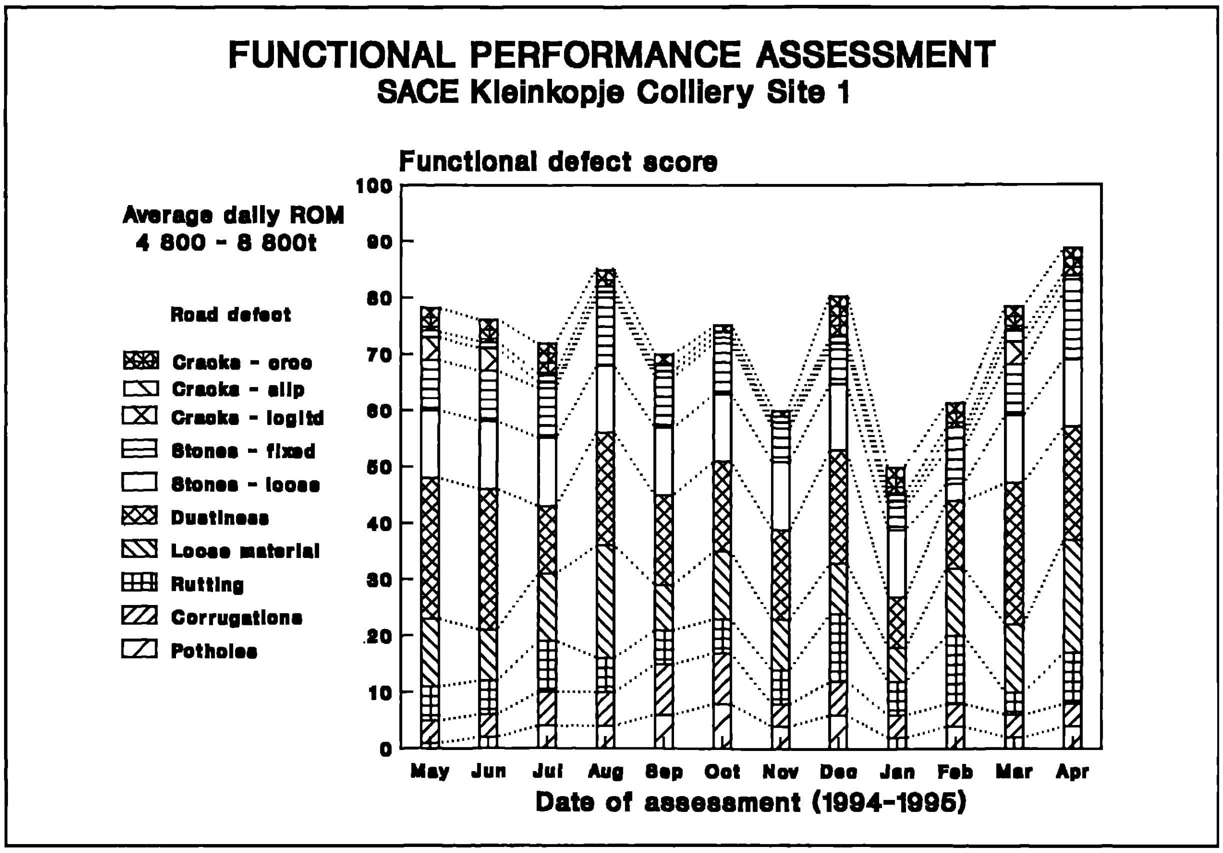


Figure 9.46 Functional Performance Assessment, Kleinkopje Colliery Site 1.

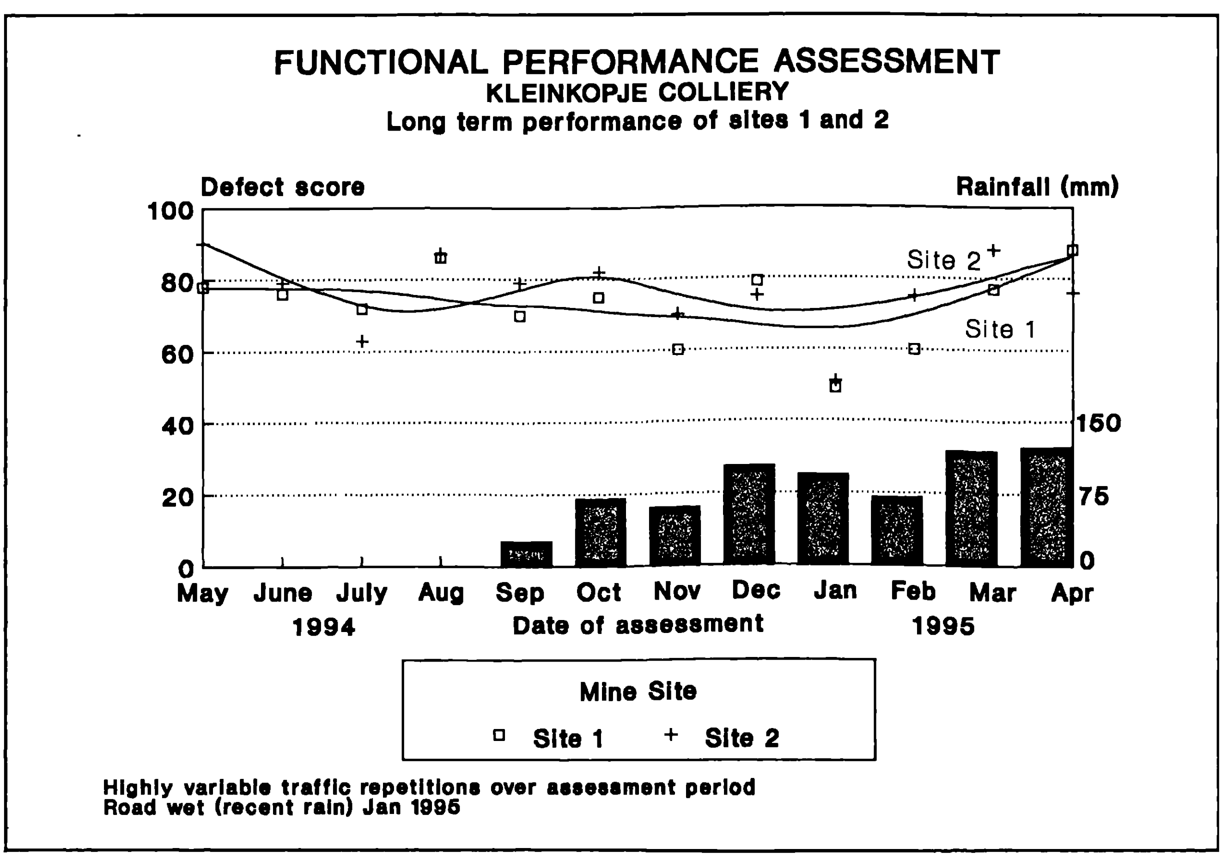


Figure 9.47 Long Term Performance Assessment, Kleinkopje Colliery Sites 1 and 2.

same trend. If the variable of days since last maintenance is included in the analysis of defect score, a trend can be deduced as shown in Figure 9.48. Although the variability of traffic volumes obscures the actual relationship, a decrease in defect scores immediately after maintenance takes place due to a decrease in dust defects generated by the blading, for between two and three days, then follows a period of steadily increasing defect scores. Figure 9.49 illustrates how individual defects vary with days since maintenance, the corrugation effect being due to stones in the wearing course which, during maintenance, forms corrugations. The relationship with traffic levels (tons/day) is not as apparent as with other mine test sites, but a reduction in the rate of increase of defect scores with traffic volume is anticipated from Figure 9.48.

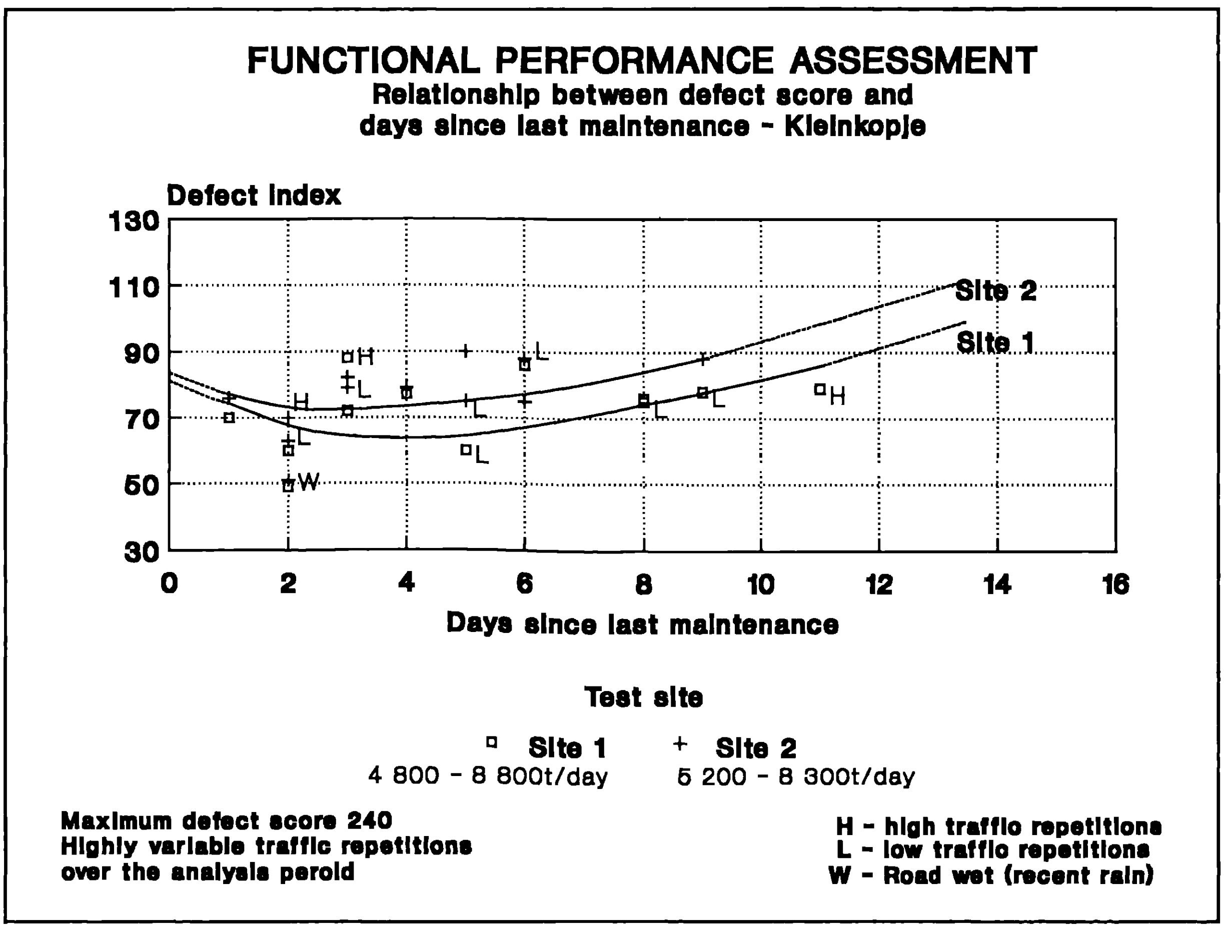


Figure 9.48 Effect of Maintenance on Defect Scores, Kleinkopje Colliery Sites 1 and 2.

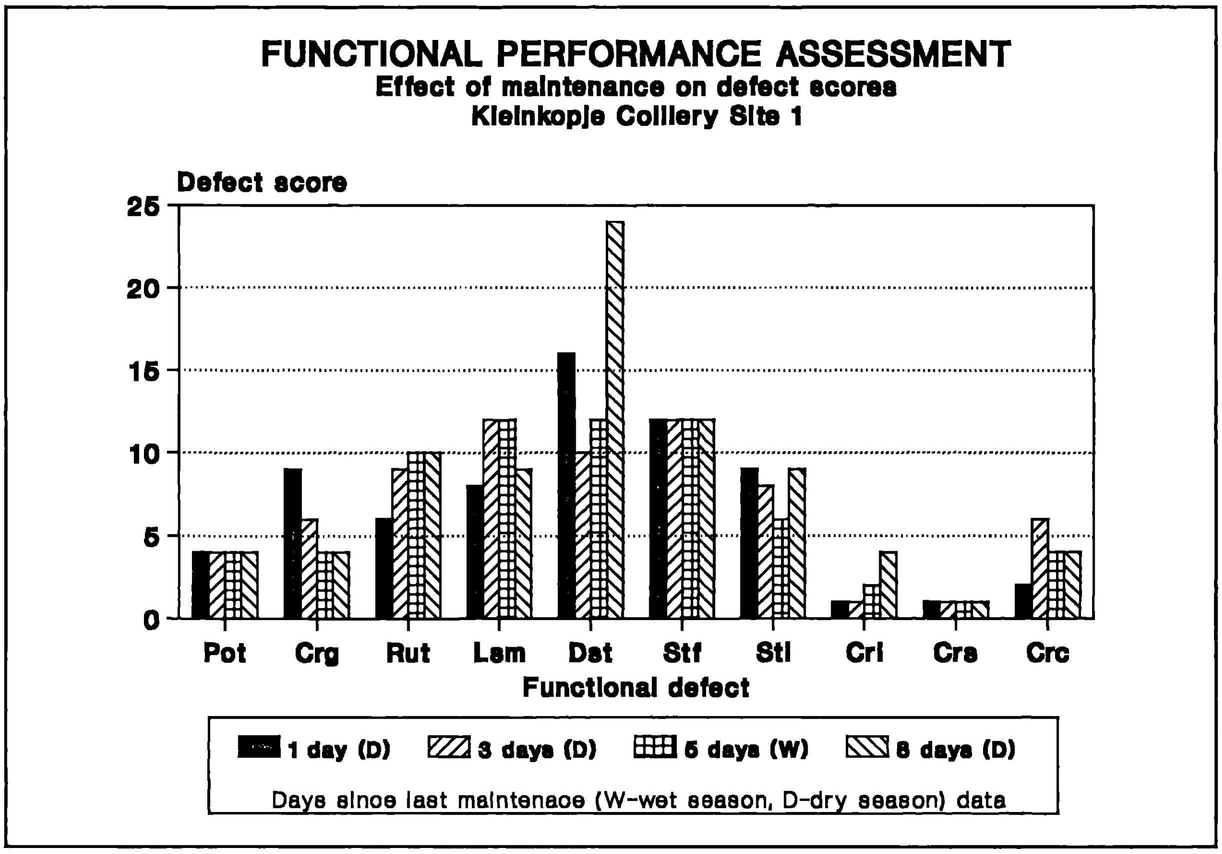


Figure 9.49 Effect of time since last maintenance on defect scores, Kleinkopje Colliery site 1.

Both level and grade sections were analysed at site 1. No major differences were observed between locations, only a slight reduction in the severity and extent of potholing, most probably due to the slightly better drainage conditions on grade and less fine loose material on the road on the unladen (downgrade) side of the road. There was not a commensurate decrease in dust defect scores due to the higher speed and wind shear velocities generated by the trucks. Typical dust defect conditions are illustrated in Figure 9.50 for a slow moving (35km/h) laden truck.

Figure 9.51 illustrates the degree of large stones in the wearing course which instigate the formation of potholes and poorly compacted areas between stones as shown in Figure 9.52.

<u>Site 2</u>

The performance of site 2 over the assessment period in terms of individual and average wet season, dry season and annual defect scores is presented in tabular form in Appendix F4.

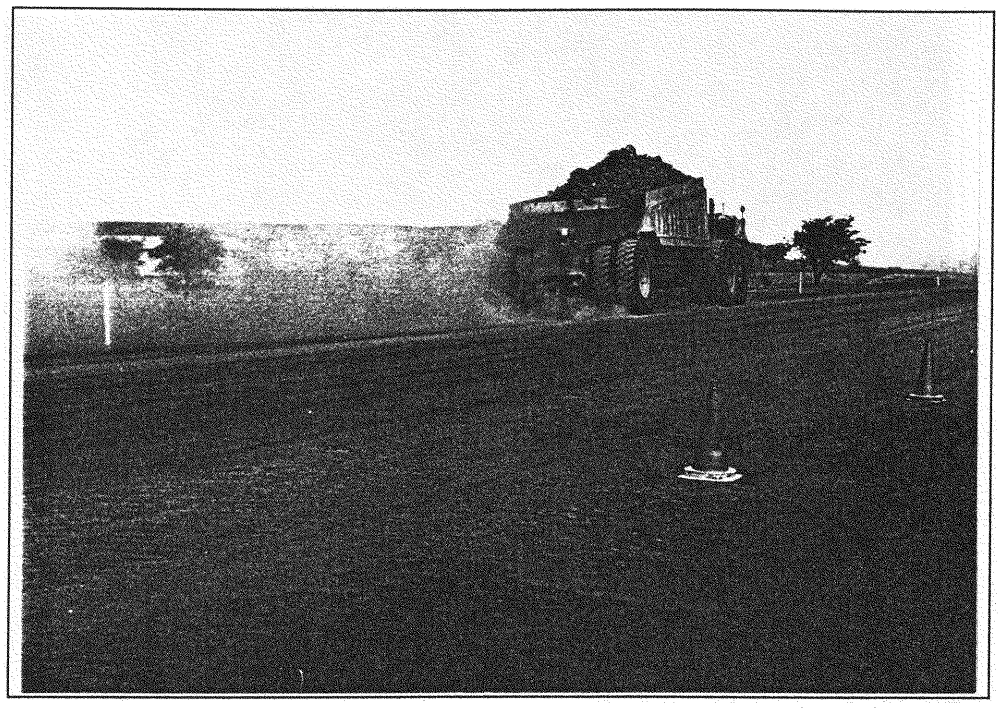


Figure 9.50 Typical dust defect problem, Kleinkopje Colliery site 1.

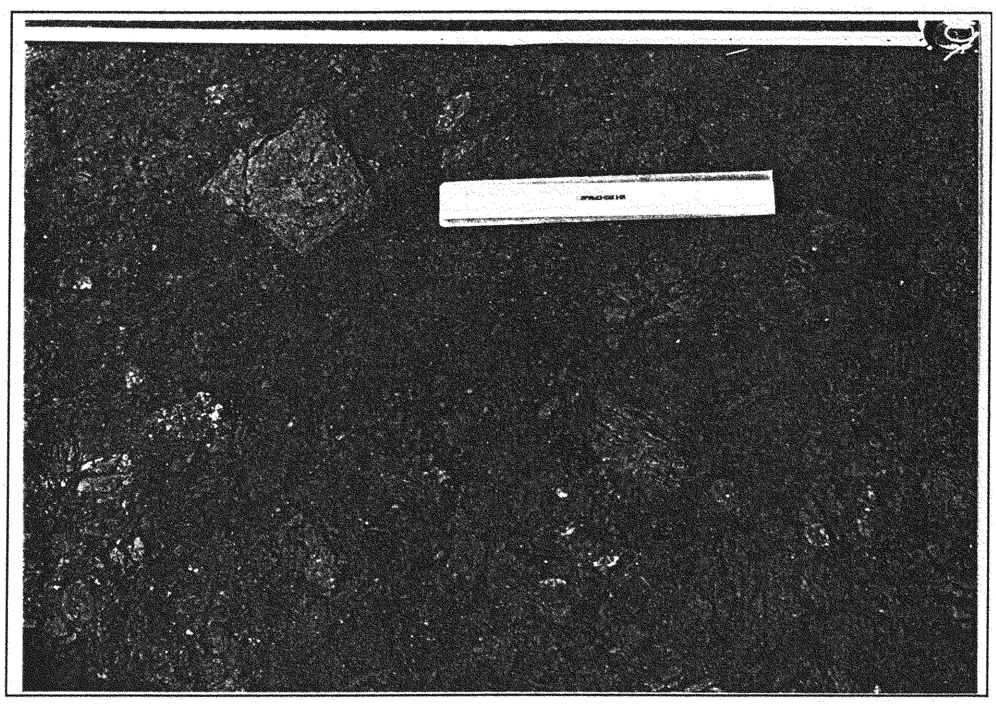


Figure 9.51 Fixed stoniness (after loose material removed), Kleinkopje Colliery Site 1.

Dustiness, loose material and loose stone defects contributed the most to the total material defect score of 76 by approx. 22%, 15% and 14% respectively. These defect scores are shown graphically in Figure 9.53 from which it is seen that although individual defect scores

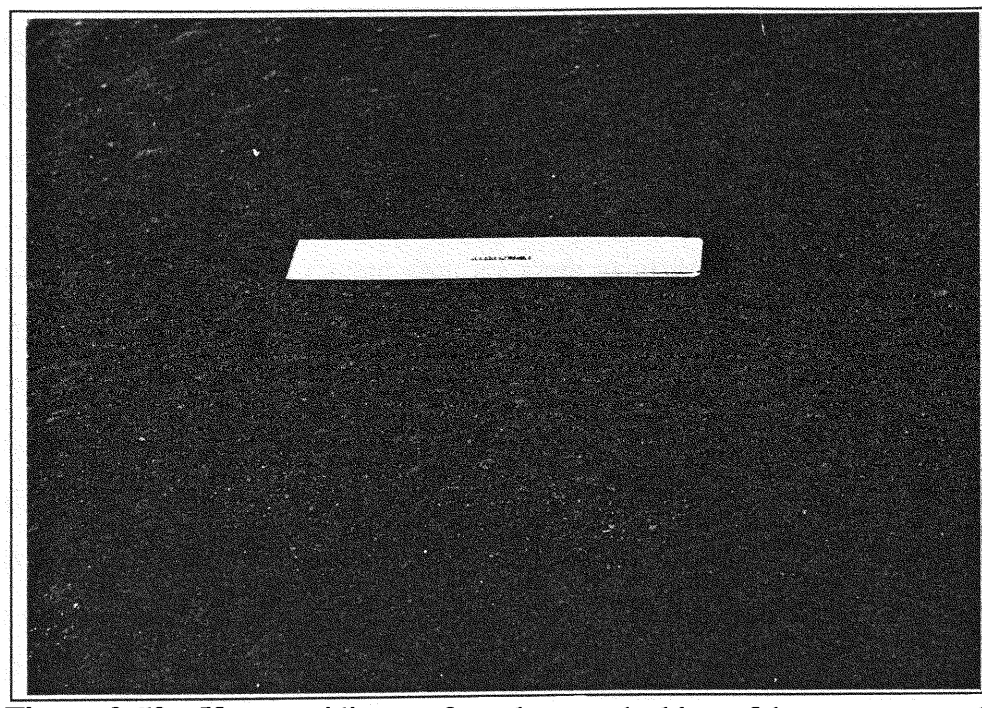


Figure 9.52 Uneven riding surface due to plucking of large stones and poor compaction of wearing course, Kleinkopje Colliery Site 1.

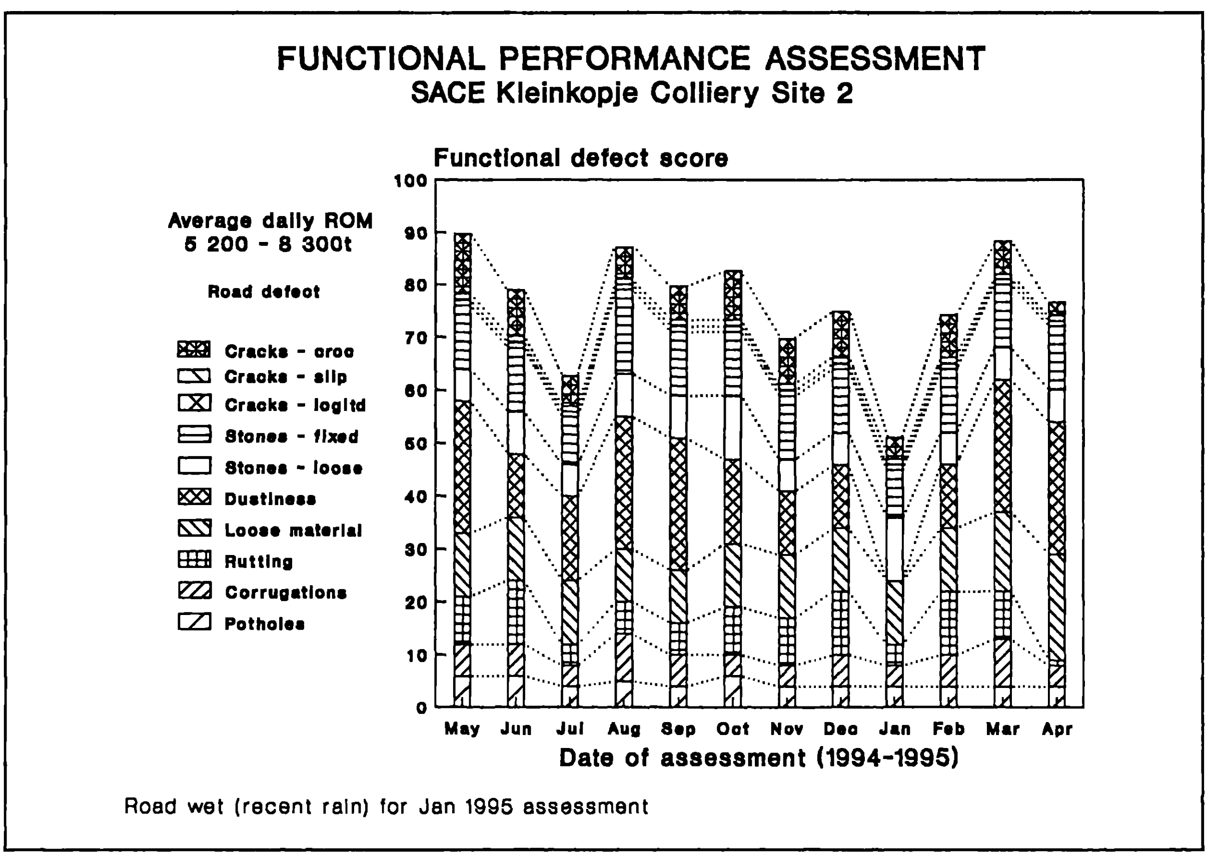


Figure 9.53 Functional Performance Assessment, Kleinkopje Colliery Site 2.

vary slightly, there is no obvious trend (excepting January 1995 assessment which shows a reduction in dust defect scores due to recent rain). An increase in loose material and fixed stoniness defect scores were observed over the wet season (Sept 1994 - Apr 1995).

Only level straight and level curved sections were available at this test site for assessment and no major differences were seen apart from a tendency of the wearing course to shear failure on the curved section of the road when wet. Little difference was observed between laden and unladen sides of the road apart from the character of the dust (associated with fine coal spillage) and a greater extent of smaller potholes or depressions on the unladen side (possibly due to material whip-out). Figure 9.54 illustrates the difference between laden and unladen carriageways (laden LHS) due to fine coal spillage (water recently applied) whilst Figure 9.55 illustrates the condition of the road after recent blading. Loose material on top of a well compacted and cemented "blad" is apparent, together with loose uncompacted material in depressions and shallow wide potholes. Cementing of the wearing course through natural chemical processes has been observed at other mine sites where ferricrete forms the wearing course material and, without scarifying, may cause layering of wearing course material that is bladed on and off the road when wet.

9.4 Summary of Functional Performance Assessment

In order to assess the utility of established performance related wearing course selection guidelines for the adoption in haul road design, the functional performance of 11 mine test sites were evaluated over a period of 12 months. The mine sites encompassed a range of traffic volumes and material types as depicted in Table 3.13 of the experimental design.

A qualitative functional performance assessment methodology was developed based on typical haul road wearing course, formation and function defects. The evaluation of these defects was based on degree and extent scores derived from consideration of the severity and occurrence of the defect as it applies to mine haul roads. The defects of potholing, corrugating, rutting, loose material, dustiness, fixed and loose stoniness and cracking were assessed in terms of degree and extent. The function and formation defects of wet and dry

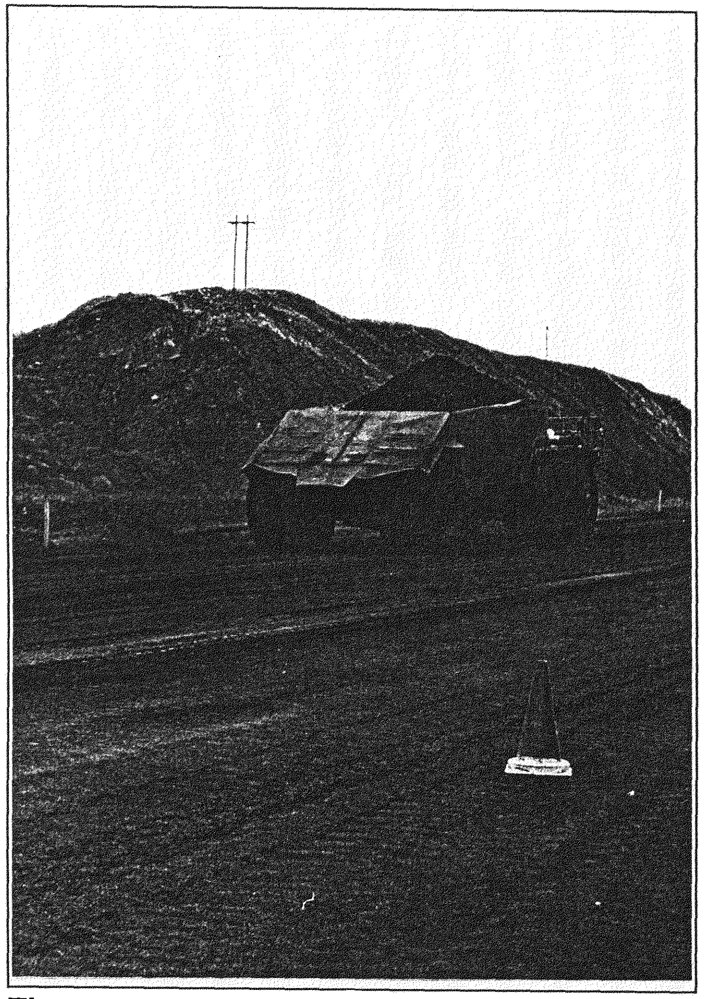


Figure 9.54 Difference in character between laden and unladen carriageways when wet, Kleinkopje Colliery Site 2.

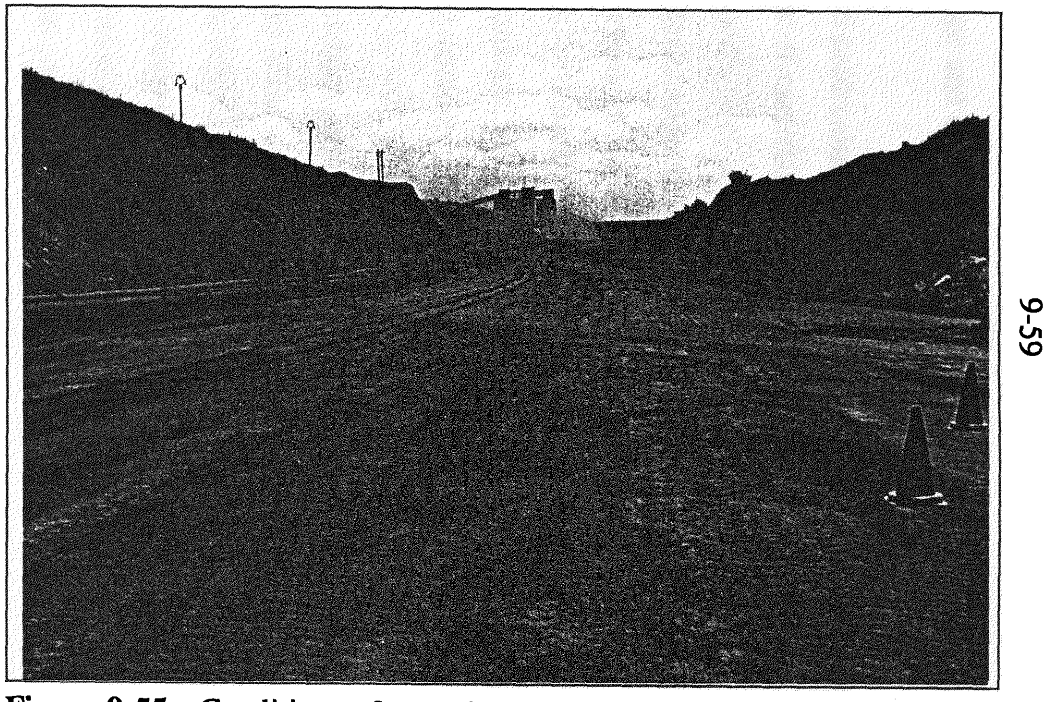


Figure 9.55 Condition of wearing course after blading, Kleinkopje Colliery Site 2.

skid resistance, drainage and erosion were assessed in terms of degree only.

Two material types are predominant in their use on the mines as a wearing course material; ferricrete and mixtures of material. The latter encompass the weathering products of basic crystalline rocks and pedocretes with the addition of ash as a binder in various quantities. Irrespective of the material type used, the general classification (according to TRH14) was that of G5-G7. CBR values (at 100% Mod AASHTO) varied between 43 and 186 and 22-59 (at 95% Mod AASHTO). Plasticity indices varied between 4-10 for all material types and grading was fairly consistent, the top size being less than 13,2mm except for mixtures of materials incorporating dolerite, where the top size was less than 19,0mm.

Functionality defects which primarily influence the choice of wearing course material selection guidelines are those concerning material, as opposed to formation or function. Material defects are therefore analysed in detail, the formation and function defects scores being used to qualify spurious measurements. The functional defects of wet and dry skid resistance are also considered from the point of view of trafficability. Whilst all weather trafficability is the main consideration for the existence of engineered unpaved roads and the choice of wearing course material, wet weather trafficability is not a critical concern for mine haul road operators since hauling operations are generally discontinued when the road churns excessively. Under the influence of prolonged soft rain, the reduction in strength associated with any wearing course material will eventually result in excessive damage to the road under the action of large haul trucks. It is not possible to select a wearing course material that, in its wet state, is sufficiently strong to prevent deformation or weakening associated with these large trucks. More critical is "short term wet weather trafficability" associated with short, heavy rain showers. Under these circumstances the road must not become excessively slippery. Dry skid resistance can be tentatively correlated with the loose material and degree of erosion defects. Thus wet and dry skid resistance, whilst forming part of the assessment, are included by implication in the analysis of the results through consideration of other associated defects. The dry skid resistance was found to be problematic only after blading of the road, which inevitably produced considerable loose material unless the formation of a "blad" (natural cementation of ferricrete material) was evident. Wet skid resistance was generally problematic, but only on a very short term basis (where water is applied for dust allaying purposes) or during heavy showers.

The major haul road functionality defects encountered were dustiness, loose material, fixed and loose stoniness and crocodile cracking. These defects exist on the road on a long term basis and are not corrected by routine maintenance (blading), the only variation being in degree of defect. Dustiness was encountered on all roads, laden and unladen carriageways, although the character of the dust is different on the unladen (faster) side of the road, coarser material being seen at the sides and between wheel tracks. On the laden side, the vehicle speed is generally lower and finer dust is seen all over the carriageway. Additionally, fine coal on this carriageway adds to the problem in terms of opacity of the dust cloud. Dust palliatives have been applied at all 11 mine sites, most usually over the winter months and this is implicitly included in the analysis.

Loose material or ravelling of the wearing course material is thought to be derived primarily from a deficiency in fine binder material. The extent to which this is born out by the correlation between defect and material properties will be established in the following Chapter. Considerable loose material is generated immediately after maintenance and critically affects dry skid resistance. The extent to which this material compacts is dependant on the cohesion and moisture conditions of the material. In general, considerable loose (fine) material was in evidence on most roads during the dry season, a slight increase in degree evident on the unladen carriageway, associated with the reduction in fine material (liberated as dust) due to the relatively higher wind shear velocities of unladen vehicles and lighter axle loads.

Loose stoniness appears to be associated with the fixed stoniness of the road, the significance of this apparent correlation being determined in the following Chapter. Little difference in defect score was seen on level or grade section, laden or unladen carriageway. In most cases it is evident that the action of haulers is to produce a shear failure around the (locally) less compacted material adjacent to the edge of the stone which eventually liberates the stone onto the road surface. This defect leads to increased road roughness, a reduction in safety and tyre life and a secondary potholing defect. Material testing results rendered a maximum material size of 19,0mm which did not correlate with field observations. Sampling techniques adopted may have unduly favoured stone-free sections.

Of the cracking defects analysed, crocodile cracking received the highest crack defect scores. Slip cracks are thought to be associated with inadequate structural performance as opposed to poor wearing course strength, except for those cracks occurring in the centre of the road which are associated with shear failure and horizontal movement of the wearing course (often exacerbated when trucks are accelerating, braking or negotiating bends). In some instances, crocodile cracking may be indicative of poor structural performance, those mine sites exhibiting excessive structural displacement also exhibited extensive crocodile cracking. However, coupled with their tendency to be less prevalent in the wet season, the plasticity of the material is proposed to be the major control; excessively plastic materials swelling and drying with changes in moisture content of the wearing course. No materials testing was carried out to determine the type of natural soil from which the local mine ferricrete developed but it may be hypothesized that ferricrete formed from clayey material (in which the nodules are inherently weaker) may be more liable to create this type of defect than material derived from sand. In terms of dustiness, there is limited evidence to support this if it is assumed that the clay derived ferricrete is liable to form more dust sized particles. The aspect of material properties and their association with a particular defect will be more fully addressed in the following Chapter.

The secondary defects associated with slip and crocodile cracking have a distinct effect on functionality in terms of the generation of plates of material and potholes. Plates are generated from crocodile cracks and/or slip cracks due to the action of haulers inducing shear failure in or under the material at specific depths. These can be associated with layering of the wearing course material and it is postulated that this results from the repeated blading of material on and off the road. Without sufficient scarifying of the surface, this material once placed on the road does not bond with the underlying material (especially if a blad is formed) and eventually shrinks and cracks to form plates which are easily lifted out of the road. Spillage of fine coal leads to a more pronounced layering effect.

The remaining defects contribute between 1%-6% to the total defect scores and whilst important in terms of the functionality of a specific road, do not require further elucidation.

The defect scores generated for each material type under specific traffic volumes and maintenance intervals, together with the effect of specific material property variables on defect scores as alluded to in this Chapter, need to be assessed statistically as a precursor to assessing the utility of established material selection guidelines in the amelioration of specific wearing course functional defects through appropriate choice of, or modification to, material property variables.

CHAPTER 10
STATISTICAL ANALYSIS AND MODELLING OF FUNCTIONAL PERFORMANCE

10.1 Introduction

The functional performance characteristics of individual mine sites were assessed qualitatively in the previous Chapter, in terms of individual defect score variations with time and maintenance activities, together with the long term performance trend over the wet and dry season. However, no predictions were made regarding the effect of traffic volume, wearing course material type, material properties or maintenance intervals on the functional performance of a particular haul road, nor was the propensity of a particular material property to contribute to a particular haul road defect analysed. This chapter 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. The emphasis with the latter analysis is the identification of material parameters as opposed to the prediction of defect scores from material property parameters.

The development of a predictive model for defect score progression with time is critical both in terms of the development of a maintenance and design model for mine haul roads and as a measure of pavement condition that can be directly associated with vehicle operating costs. The defect score at a particular point in time is a reflection of the type of wearing course material used and its engineering properties, the level of maintenance, season and traffic volumes. Paterson (1987) describes three fundamental mechanisms of deterioration namely wear and abrasion, deformation and erosion and concludes that the modes of deterioration differ with the seasons and Visser (1981) categorises these modes in terms of prominent deterioration characteristics. From the analysis of defect scores presented in Chapter 9 it was concluded that whilst no significant difference in wet and dry season average defect scores were discerned, a qualitative analysis of the long-term functional performance implied a marginal increase in defect scores over the wet season. The comparatively frequent watering and blading activities on mine haul roads are thus thought to obscure any significant seasonal variations. Thus in the analysis of the effect of maintenance on defect scores which follows, a combination of defect scores and maintenance interval data over both seasons is adopted and seasonality ignored.

Whilst a model of defect score progression is useful to predict and compare the functional performance of a particular wearing course material (in terms of its engineering properties and the traffic volume on the road) with the acceptability requirements of the road-user it is also necessary to determine the propensity of a particular material to form specific functional defects, also through consideration of the materials engineering properties and the average defect score associated with the material type. Once road-user acceptability limits for each defect are determined, the corresponding limits for the significant material parameters implicated in each defect may be resolved through consideration of the individual defect score models.

10.2 Prediction of Defect Score Progression

The qualitative derivation of the relationship between defect score and maintenance interval was addressed in Chapter 9 from where the model in Figure 10.1 was derived. When the action of traffic on the haul road is considered in terms of this model, four distinct actions can be hypothesised as shown in Figure 10.1;

(A) Immediately following maintenance there will be a traffic induced reduction of loose material and dust defect scores such that the post-maintenance defect scores decrease overall.

(B) A minimum defect score will be acheived where the progression changes from decreasing to increasing.

(C) The increasing traffic volumes and dynamic loadings imposed on the road, together with an increase in abrasion result an increase in the defect scores until traffic speed slows and wheel paths change to avoid damaged sections.

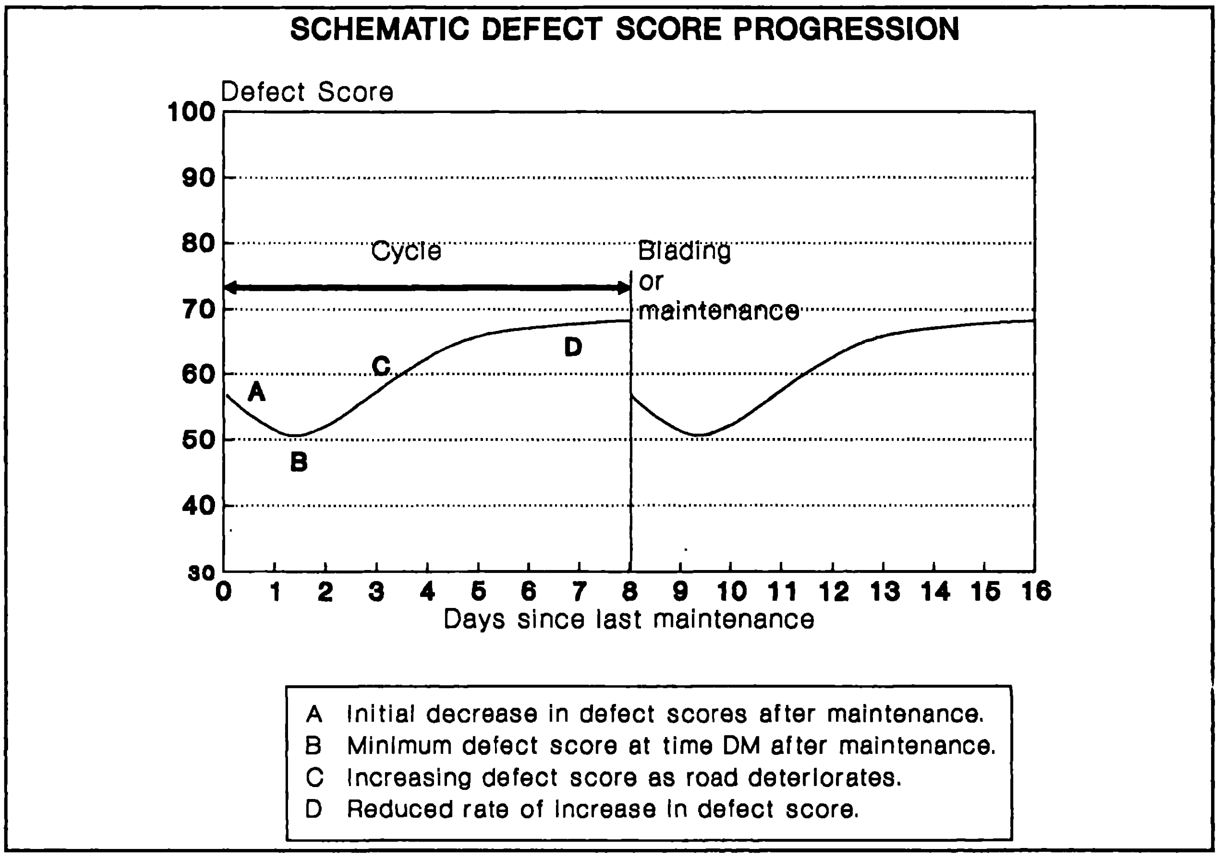


Figure 10.1 Schematic illustration of the development of defect score on a haul road.

(D) At this point the defect score would remain essentially constant.

This hypothesis and model is similar to those proposed by Visser (1981) and Paterson (1987) over a single cycle (the period between bladings) although the latter two models were based on the prediction of roughness (as measured by a response type road roughness instrument) and thus would not recognise dust, loose material and other such defects directly.

In the selection of a model for defect score progression, a piecewise combination of two exponential type curves was chosen to represent the decreasing and increasing rate of change of defect score with time (or traffic volume). Using a logarithmic transformation of defect scores, a regression function was developed based on a linear combination of the independent variables for the rate of defect score decrease (LDDD) and increase (LDDI). In addition, an expression for the minimum defect score after maintenance (DSMIN) was sought together with its location in terms of days since maintenance (DM), both assumed to be linear combination of the independent variables, as illustrated in Figure 10.2.

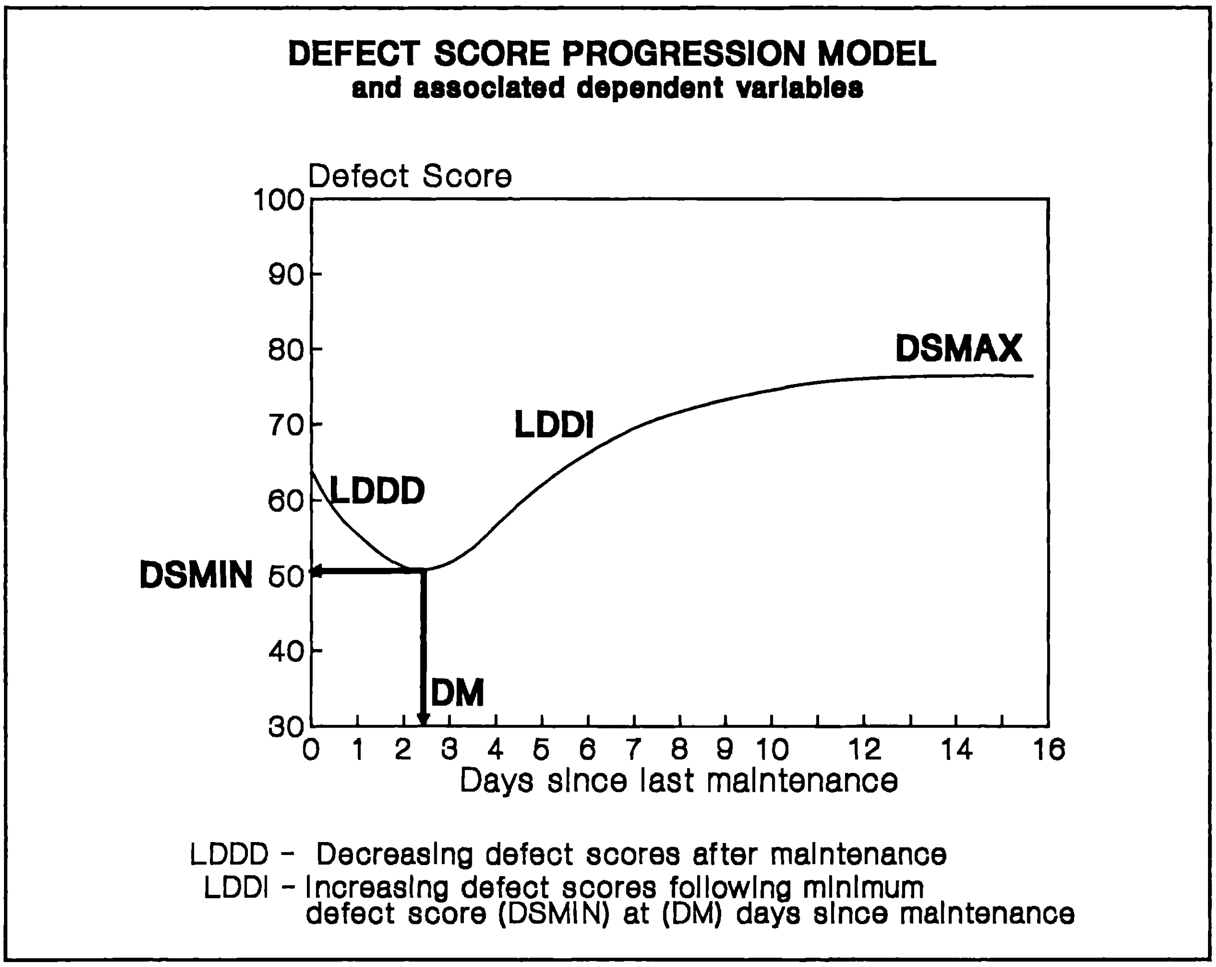


Figure 10.2 Selection of model and dependant variables for defect score progression

The rate of change in defect scores was calculated over the maintenance cycle and these values used as the dependent variables in a multiple correlation analysis in order to identify the significant factors affecting defect progression. The independent variables listed in Table 10.1 were evaluated.

A regression analysis was conducted using a least squares approach to determine the best-fit equation between the variables. In using such a regression technique to derive statistical inferences regarding the association between dependent and independent variables the assumptions underlying the formulation of a best-fit linear model include linearity in the parameters (but not necessarily in the independent variables), independence of errors, constant variance and the normal distribution of the data points constituting a variable. The

Table 10.1 Independent Variables Used in the Regression Analysis of LDDD and LDDI

INDEPENDENT VARIABLE	DESCRIPTION
KT	Average daily tonnage hauled (kt)
M	Wearing course material type; 0=ferricretes 1=mixtures of materials
P075	Percentage of material passing 0,075mm sieve
DR	Dust ratio, defined as; $\frac{P075}{P425}$ where P425=percentage of material passing the 0,425mm sieve
PI	Plasticity index
CBR	100% Mod. California Bearing Ratio of wearing course material
GC	Grading coefficient, defined as; $\frac{(P265-P2)xP475}{100}$ where P265=percentage of material passing the 26,5mm sieve P2 =percentage of material passing the 2,0mm sieve P475=percentage of material passing the 4,75mm sieve
SP	Shrinkage product, defined as; $LSxP425$ where LS= Bar linear shrinkage
PL	Plasticity limit
D	Days since last maintenance
DM	Days between last maintenance and minimum cycle defect score
DSMIN	Minimum defect score in cycle

selection and assessment of a best-fit equation was based on the consideration of the Pearson correlation coefficient (R^2%) value in which 100% indicates perfect correlation and 0% no correlation. In general, a lower R-squared value increases in significance as the sample size increases. Additionally, the standard error of estimate (SEE) was used as a measure of scatter about the regression curve (analogous to the standard deviation). Where the sample size is large, the 95% confidence limits about the mean may be estimated as double the standard error of estimate. The F-statistic, being a ratio of explained (model derived) and unexplained (error derived) variances indicates the overall statistical significance of the model and was also used as a means of assessing the significance of the model, higher F values indicating a more significant model for larger sample sizes. Students' t-statistics were also assessed to determine the significance of each independent variable in the model.

For the exponential model of rate of defect score decrease after maintenance the following variables were found to be significant:

$$LDDD = 1{,}261 + DM(0{,}000121.CBR.KT - 0{,}02954.GC + 0.009824.SP.DR) \quad (10.1)$$

This model has an R-squared value of 26%, F value of 3,87 which is significant at the 2% level for a sample size of 25 which incorporated those sites at which decreasing defect scores following maintenance were recorded. For the standard error of the model of 0,538, the approximate 95% confidence intervals for a rate of change in defect score decrease of 10 per unit time lie between 3,4 and 29,3. Full statistics for the model are given in Table 10.2.

To establish the location of the minimum defect score after maintenance (DSMIN) time-wise (DM) an analysis was conducted using DM as the dependent variable. However, no significant model could be derived from the independent variables analysed and recourse was made to the modal value of DM=2 days to locate the position of DSMIN. The regression of DSMIN on the independent variables rendered the following model:

$$DSMIN = 37{,}9146 - 0.15799.KT + 12.7093.M + 1{,}3836.GC - 0{,}08752.SP \quad (10.2)$$

Table 10.2 Defect Score Progression Model Statistics

STATISTICS OF MODEL ESTIMATION FOR LDDD, DSMIN, LDDI AND DSMAX								
	STATISTICS OF INDEPENDENT VARIABLES				RANGE OF VALUES			
MODEL	VARIABLE	STANDARD ERROR	t-VALUE	SIGNIF LEVEL OF t-VALUE	MEAN	STD. DEV	MIN	MAX
1 LDDD	Intercept	0,25901	4,87	0,0001	-	-	-	-
	DM.KT. CBR	0,00005	2,28	0,0331	3393,64	823,29	288,0	14100
	DM.GC	0,01025	-2,87	0,0091	51,48	25,77	21,3	114,8
	DM.SP.DR	0,02919	3,36	0,0029	116,25	66,95	28,8	256,0
2 DSMIN	Intercept	5,38061	7,05	0	-	-	-	-
	KT.PI	0,01194	-13,23	0	99,48	67,68	47,6	250,0
	M	2,06432	6,15	0	-	-	-	-
	GC	0,18470	7,49	0	28,80	4,29	21,3	36,3
	SP	0,02220	-3,94	0,0002	143,97	45,05	72,0	198,0
3 LDDI	Intercept	0,08749	20,49	0	-	-	-	-
	D.KT	0,00078	2,9	0,005	88,14	88,34	6,8	450,0
	D.DR.GC	0,00295	3,46	0,0009	87,46	57,79	9,9	241,2
	D.GC	0,00164	-6,62	0	171,33	116,89	24,8	497,8
4 DSMAX	Intercept	2,98887	11,71	0	-	-	-	-
	M	1,29954	20,60	0	-	-	-	-
	KT	0,03465	-16,37	0	-	-	-	-
	GC	0,10207	16,12	0	-	-	-	-
	SP	0,02769	14,78	0	-	-	-	-
	PI	0,58224	-18,73	0	-	-	-	-
INFERENCE SPACE LIMITS FOR INDEPENDENT VARIABLES USED IN MODELS (1) TO (4)								
KT					20,88	16,20	6,0	50,0
DR					0,48	0,08	0,4	0,6
GC					28,4	4,29	21,3	36,3
CBR					73,96	23,54	46,0	132,0
SP					143,97	45,05	72,0	198,0
PI					6,56	1,78	4,0	10,0
D					6,20	4,39	1,0	19,0
DM					1,8	0,86	1,0	4,0

This model has an R-squared value of 80%, an F value of 69 which is significant at better than the 0,1% level for a sample size of 11. For the standard error of the model of 5,529 the approximate 95% confidence intervals for a minimum defect score of 30 lie between 19 and 41. The goodness of fit between predicted and observed minimum defect score is illustrated in Figure 10.3. Full statistics for the model are given in Table 10.2.

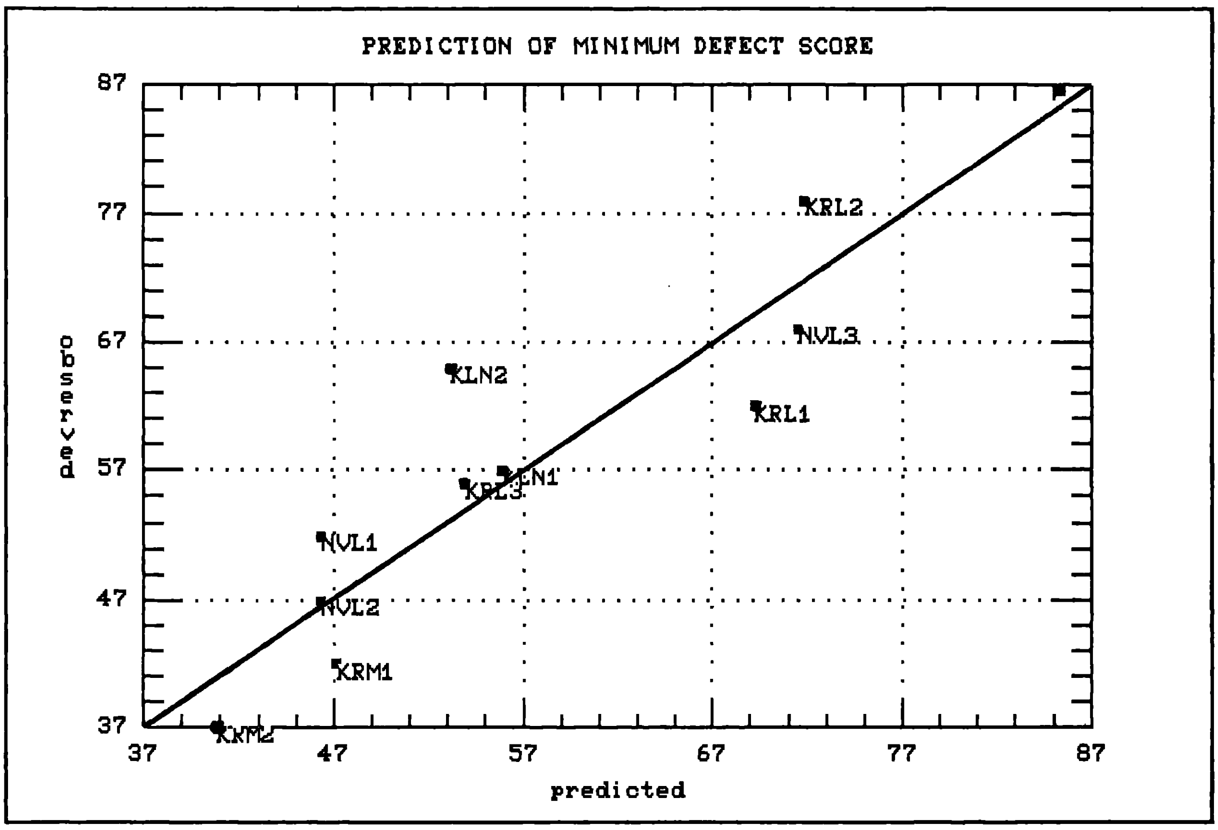


Figure 10.3 Goodness of fit for model (2) for DSMIN

The logarithmic value for the rate of defect score increase (LDDI) was analysed using data from beyond the location of DSMIN. The following model was derived:

$$LDDI = 1{,}7929 + D(0{,}002276.KT + GC(0{,}01029.DR - 0{,}010887)) \qquad (10.3)$$

This model has an R-squared value of 71%, an F value of 55 which is significant at better than the 0,1% level for a sample size of 67 (11 sites, 12 records each, excepting those in which DM$\leq$2). For the standard error of the model of 0,387 the approximate 95% confidence intervals for a rate of change in defect score increase of 10 lie between 4,6 and 21,7. The goodness of fit between predicted and observed minimum defect score is given in Figure 10.4. The model tends to under-predict the rate of defect score increase beyond approximately 5,5 per day. Only a limited number of sites exhibited such large rates of change and may be associated with extreme, as opposed to average, conditions on the road over a short period. Full statistics for the model are given in Table 10.2. The model predicts a greater increase in LDDI for increasing average daily tonnages hauled, increasing grading coefficient and dust ratio values. The model also indicates that haul road defect scores will increase with time, even in the absence of heavy traffic, purely as a result of wearing course material environmental degradation with time.

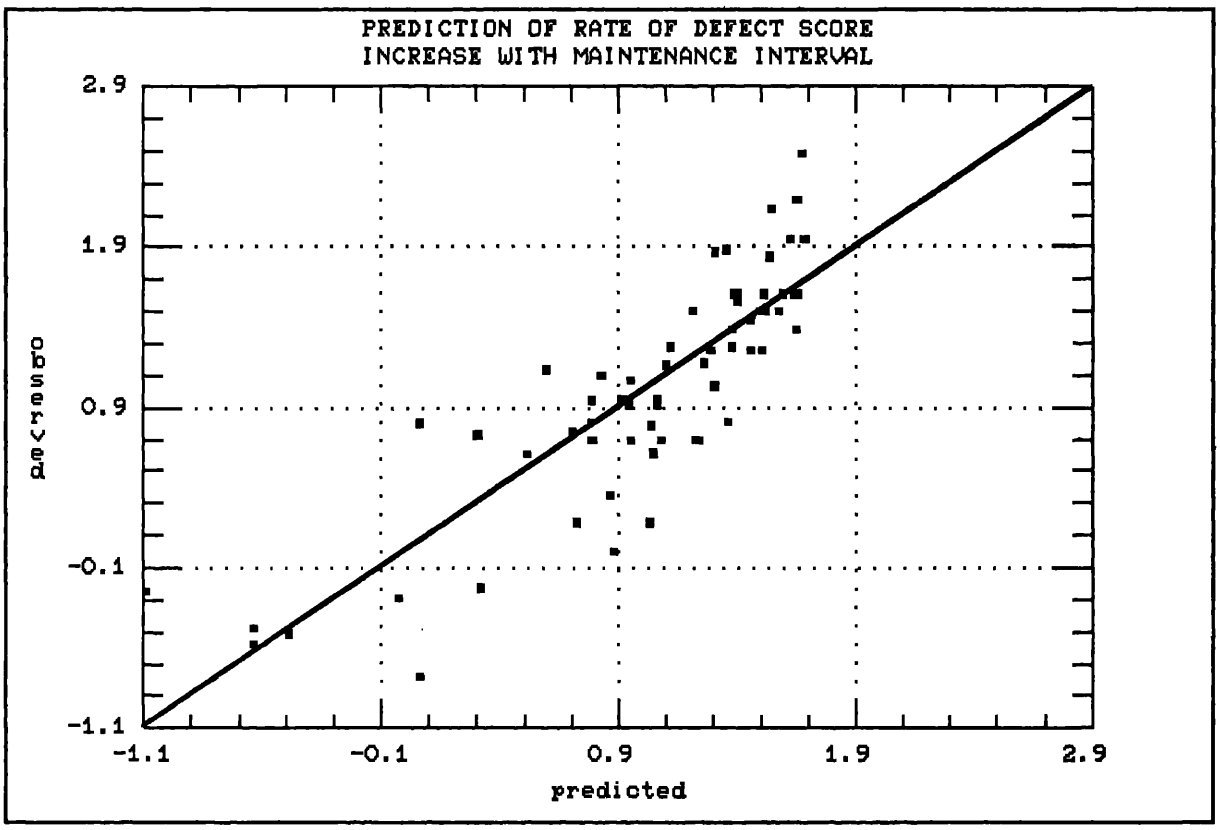


Figure 10.4 Goodness of fit for model (3) for LDDI

The predictive models given in Equations [10.1] to [10.3] together with the assumption of the modal time since maintenance for the location of the minimum defect score enable the functional response of a mine haul road to be modelled in terms of rates of decrease and, more importantly, rates of increase in defect score with time and traffic volumes. The models incorporate material property parameters together with traffic volume and, for model [10.2] additionally the material type parameter. No attempt was made to analyse the effects of defect score after blading, nor the association between maximum defect score and defect score after maintenance. Both Visser (1981) and Paige-Green (1989) make the comment that roughness after maintenance (which may be likened to defect score) is mainly a function of the expertise of the grader operator whilst Paterson (1987) considered the roughness after blading as being a function of operator experience linked with a material effect on the effectiveness of blading. The data collated in this analysis does not permit any reliable assessment of the effect of maintenance on defect scores but it is observed that maintenance frequency does not appear to increase with time thus establishing the return of the road defect score to similar levels after maintenance. This is supported from the data presented in Chapter 9 from which it is seen that a reasonable model can be qualitatively predicted from the combination of 12 months observations at any one test site.

The upper bound to the logarithmic value for the rate of defect score increase (LDDI) was estimated from a regression of maximum defect score (DSMAX) values. The following model was derived:

$$DSMAX = 35{,}0249 + 26{,}7827.M - 0{,}5672.KT + 1{,}6508.GC + 0{,}4464.SP - 10{,}9393.PI \quad (10.4)$$

This model has an R-squared value of 93%, an F value of 157 which is significant at better than the 0,05% level for a sample size of 67. For the standard error of the model of 2,694 the approximate 95% confidence intervals for a maximum defect score 80 lie between 74,6 and 85,4. Full results are given in Table 10.2.

One of the major objectives of defect score prediction was to compare the proclivity of various types of materials to deteriorate over time and the proposed model should be minimised to identify the best of a range of materials. To predict haul road functional performance for use in a maintenance and design system a datum of minimum defect score (DSMIN) after two days is proposed from which the defect score will increase. Referring to Figure 10.1, the model then commences from point B on the diagram. The prediction model [10.3] is compared in Figure 10.5 with typical mine site defect score progression, using model [10.3] bounded by models [10.2] and [10.4]. Full results for the remaining mine sites are given in Appendix G1. Figure 10.6 illustrates the effect of traffic volume (kt per day) variation on defect score progression for one particular set of material property and minimum defect score values. As can be seen, if an intervention level (or maximum acceptable defect score) of 70 is used, given a monthly production of 230 000t a maintenance interval of 13 days is advocated. When the monthly tonnage hauled increases to 1 150 000t a maximum maintenance interval of seven days is implicated for the given wearing course material parameters used in the model. Model [10.3] predicts an increase in the rate of deterioration even in the absence of traffic as a result of the effect of the dust ratio of the material. The grading coefficient appears to be negatively correlated with deterioration rate, most probably due to a reduction in the ravelling defect score over the limited inference space of the data. As regards the prediction of the minimum defect score (model 10.2), traffic volume and plasticity index are negatively correlated with the minimum score, indicating that traffic is an important factor in ameliorating maintenance induced defects such as loose material, dustiness, etc. The shrinkage product is also negatively correlated, indicating an increase in fine material may be associated with reduced defect scores associated with ravelling, corrugations and loose material. The grading coefficient in this case acts to increase the minimum defect score as the material tends toward a gap-graded gravel or larger, a fact reinforced by the inclusion of the material type indicator which signifies that mixtures of material will lead to higher minimum defect scores if all other factors are equal. This may be deduced in part from consideration of the New Vaal data where the dolerite material in the wearing course plays a significant role in functional performance, especially the larger fraction.

Models for predicting the rate of deterioration of unpaved roads based on an assessment of roughness (as opposed to defect scores) have been developed by Visser (1981), Paterson and Watanatada (1985) and Paige-Green (1989) and all these models show low R-squared values with statistically significant correlations by virtue of the large sample size. Paterson (1987) identifies high prediction errors (95^{th} percentile confidence intervals of 20 to 40 percent) as being typical of these types of study and ascribed them to the large variability in material properties, drainage and erosion. Similar effects are proposed for the models presented here with the exception of material properties which are defined over a much smaller inference space than the previous studies, which may limit the applicability of the models where materials significantly different from those encountered during testwork are to be assessed.

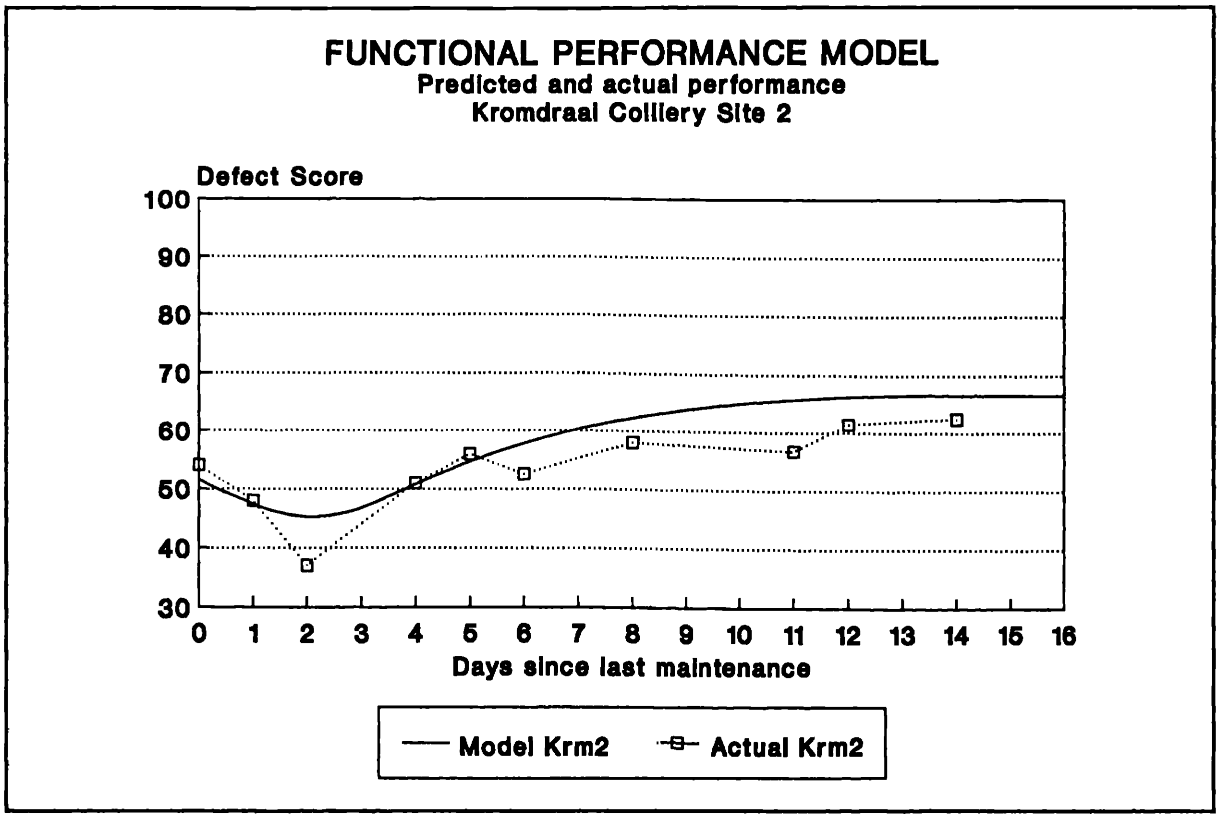


Figure 10.5 Estimation Characteristics of Prediction Model for Rate of Increase in Defect Score as Applied at Kromdraai Mine Site 2.

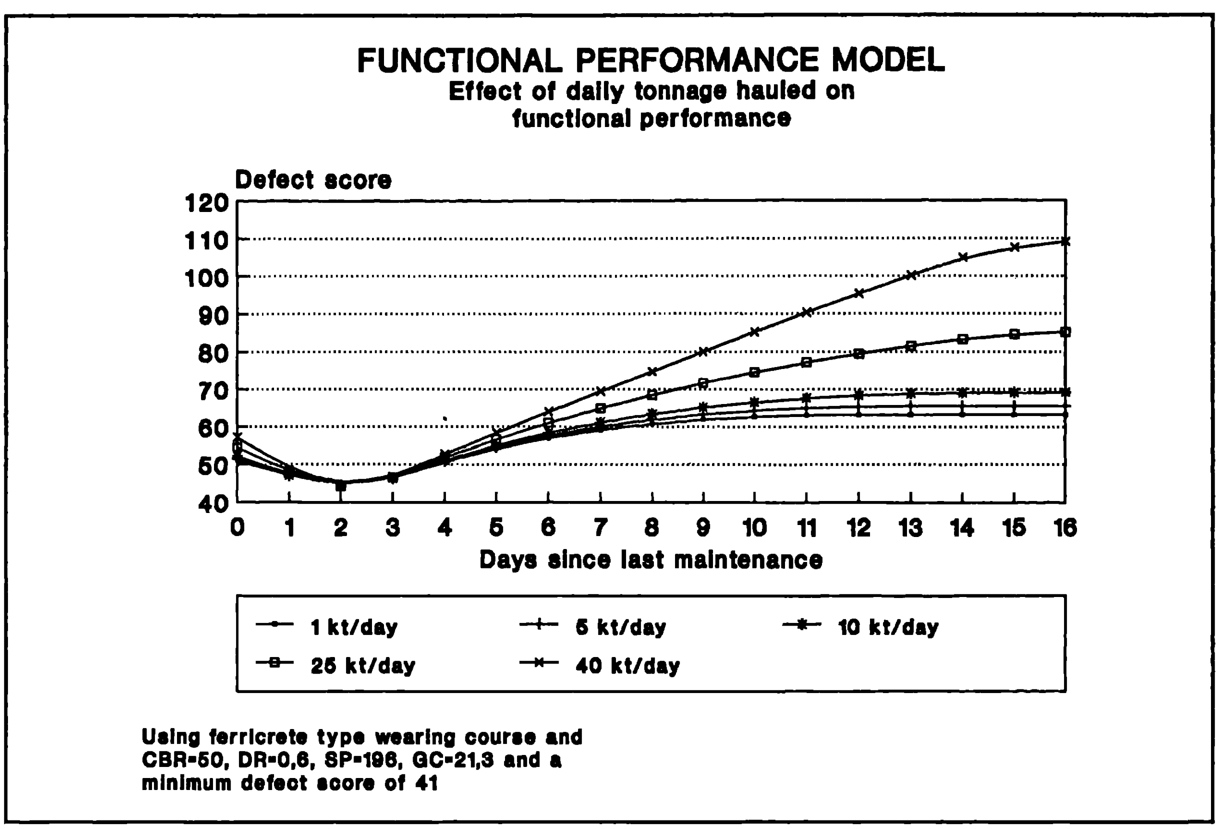


Figure 10.6 Effect of Increasing Traffic Volume on Defect Score Progression.

Despite these limitations it may be concluded that wearing course geotechnical properties, especially the particle size distribution and plasticity, together with traffic volume, are the most important material parameters with regard to the prediction of deterioration progression.

10.3 Effect of Material Properties on Individual Defect Score Progression

The objective of this analysis was to identify the material properties which affect the functional performance of the various groups of wearing course material analysed. The overall functional performance may be considered as a summation of the individual haul road defect scores. In Chapter 9 a qualitative estimation of the variation in individual defect scores was made from which two modes of progression may be hypothesised;

(i) An increase in the individual defect score with time

(ii) A decrease in the individual defect score with time.

An analysis of the rate of change in defect score with days since last maintenance was conducted to determine the nature of the increase or decrease in defect score with time. It was assumed that each test site analysed exhibited a "base" or reference minimum functionality that was particular to each site, being a function of construction technique, maintenance frequency and operational characteristics. This minimum functionality was determined from the minimum overall defect score (DSMIN in Figure 10.2) and the corresponding individual minimum or maximum (dependant on the model chosen for each defect) scores at that point in time (DM in Figure 10.2).

The rate of change in individual defect scores from the individual site and defect minimum or maximum was then determined for each defect of the 11 defects described in Chapter 9.2. Appendix G2 contains the graphical results of the analysis from which three modes of progression are seen. Figure 10.7 illustrates a typical exponentially reducing rate of corrugation defect score increase with time. The isolated negative rates are ascribed to Kriel Colliery site 2. Blading over large stones in the wearing course produces a high corrugation defect score immediately after maintenance which reduces with time and traffic. In addition, the defect scores of potholing, rutting, loose stoniness and longitudinal, slip and crocodile cracking are seen to progress in a similar manner. Figure 10.8 illustrates the second mode of progression in which loose material defect scores are seen to reduce exponentially with time. This progression was observed qualitatively in Chapter 9 and ascribed to blading. From Figure 10.7 there is some evidence to support the concept of "blad" formation associated with ferricrete materials since very few of the mine sites with ferricrete wearing course materials remediate after blading (less loose material produced) whereas mixtures of materials, in the absence of a "blad", produce more loose material immediately after blading. This material is then compacted under the action of traffic resulting in an overall reducing rate of defect score progression. In addition, the defect scores of dustiness are assumed to progress in a similar manner. Figure 10.9 illustrates the third option in which no clear progression may be determined; sites exhibiting both positive and negative rates of progression. In addition, no distinction between wearing course material types can be made. The defects of wet and dry skid resistance both exhibited equivocal progression rates.

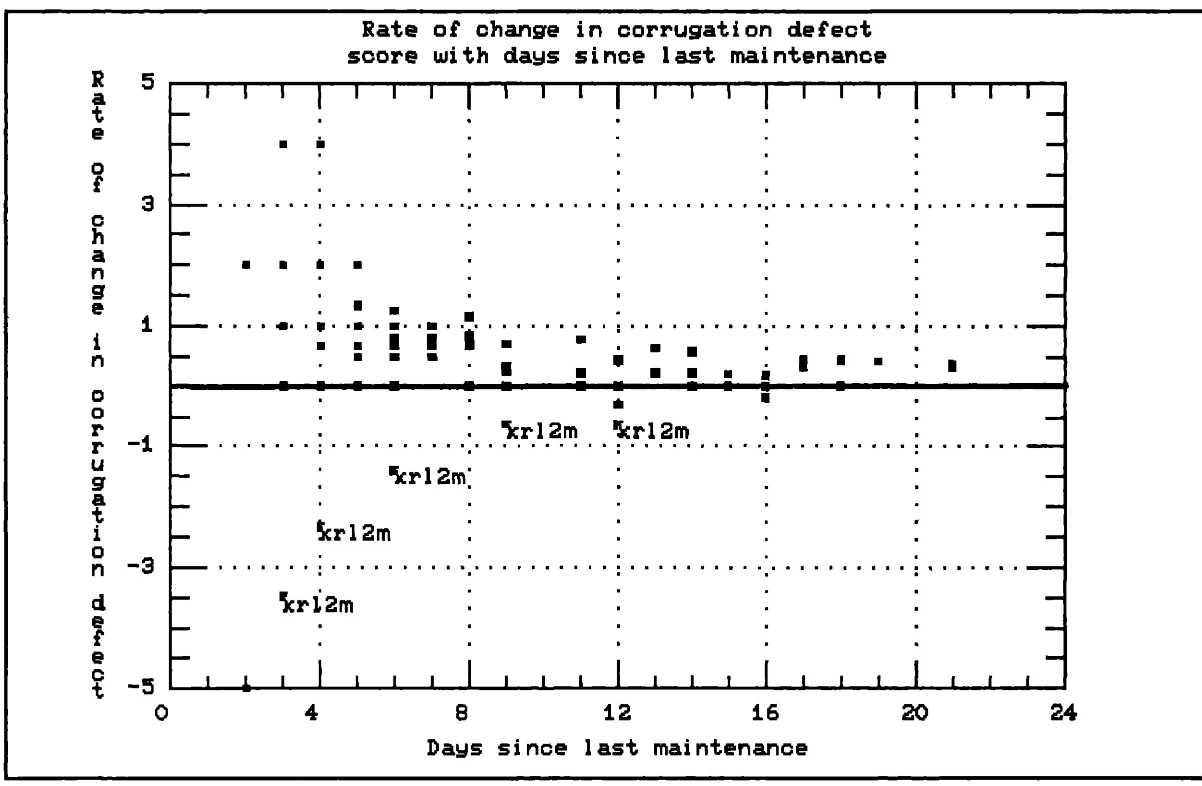


Figure 10.7 Rate of change of corrugation defect score with days since last maintenance.

The exponential model chosen to explain the various rates of defect score progression enabled a multiple correlation and multiple linear regression analysis to be conducted on the transformed rates of progression, using linear combinations of material properties, traffic

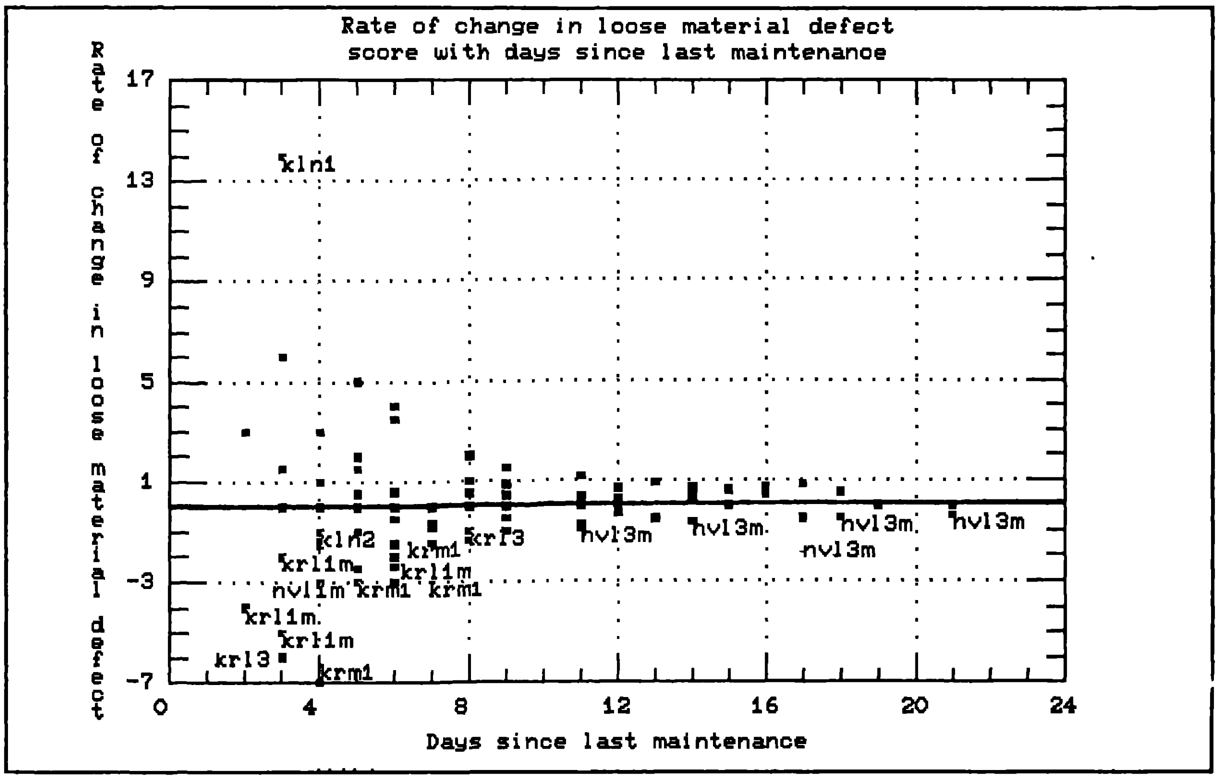


Figure 10.8 Rate of change of loose material defect score with days since last maintenance.

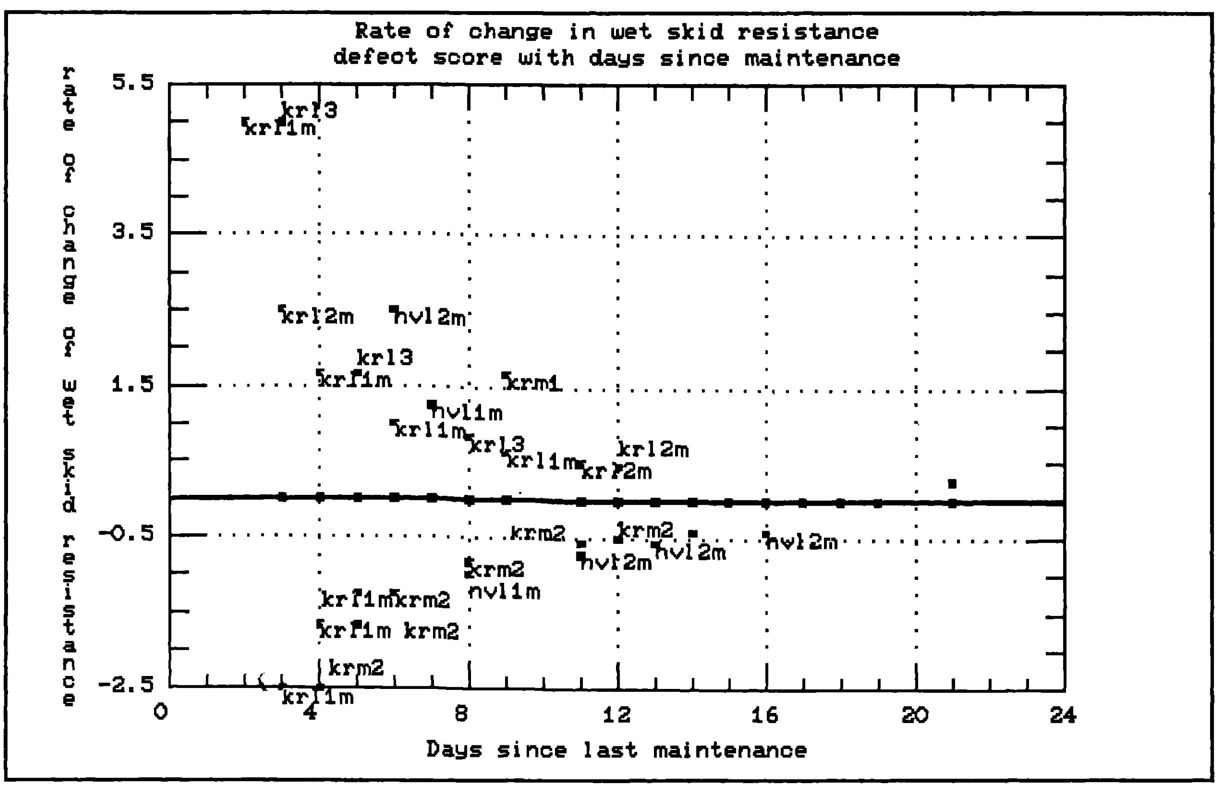


Figure 10.9 Rate of change of wet skid resistance defect score with days since last maintenance.

volume, season and rainfall with days since last maintenance and as the independent variables. When the material property mean and standard deviation values were compared with individual site parameter values given in Tables 3.9-3.12, no statistically significant difference between individual test site materials or between material type groups was found. It was thus considered feasible to group material data from each test site under the additionalassumption that whilst material group (as an independent variable) may contribute to the correlation between defect score and material properties, it would contribute little in terms of identifying those material properties with a propensity to form that defect, assuming a similar mode of defect formation, irrespective of material type. The independent variables used in the analysis are summarised in Table 10.3.

Previous studies concerning the effect of material property parameters on functionality were assessed as a first step in identifying the independent variables likely to be associated with a particular defect. Netterberg (1985) describes three basic classes of materials after compaction (following Yoder and Witczak, 1975) based on an aggregate with a deficiency, sufficiency or excess of fine material. According to Netterberg, most local road building materials fall into categories of deficient or excess fines, the former being difficult to compact and have a low surface shear strength, the latter being easier to compact but likely to be unstable when wet. Additionally, excessive clay material was associated with poor wet skid resistance and trafficability together with the tendency of the wearing course material to form slip and crocodile cracks under vehicle acceleration or deceleration. A deficiency in cohesive material was associated with ravelling and the generation of excessive loose material.

Olmstead's chart (Wooltorton, 1954) as discussed in Chapter 2.3 also indicates that both grading and plasticity are important parameters in assessing the functionality of various wearing course materials, although the defects alluded to in the chart are not as comprehensive as the set of functional performance defects addressed here. Mitchell, Peltzer and van der Walt (1979) presented details of natural gravel wearing course material performance (in terms of behavioral tendencies) which are summarised in Table 10.4, based on the Natal Provincial Authority materials manual (NPA, 1961). Again plasticity (liquid limit and plasticity index) and grading are recognised as important parameters controlling

Table 10.3 Independent Variables Used in the Regression Analysis of Material Property on Individual Defect Score Progression

INDEPENDENT VARIABLE	DESCRIPTION
R	Average monthly rainfall (mm)
S	Seasonal indicator; 0=dry season (April-September) 1=wet season (October-March)
D	Days since last maintenance
M	Wearing course material type indicator; 0=Ferricretes 1=Mixtures of material
KT	Average daily tonnage hauled (kt)
P132	Percentage of material passing the 13,2mm sieve
P075	Percentage of material passing the 0,075mm sieve
DR	Dust ratio (as defined in Table 10.1)
LL	Liquid limit (%)
PI	Plasticity index (%)
LS	Bar linear shrinkage (%)
DENS	Dry density (kg/m^3)
OMC	Optimum moisture content (%)
CBR	100% Mod. California Bearing Ratio of wearing course material
GC	Grading coefficient (as defined in Table 10.1)
SP	Shrinkage product (as defined in Table 10.1)
PL	Plastic limit

functionality. The authors note in addition that laterites (ferricretes) exhibiting low plasticity tend to corrugate whilst those with a high plasticity tend to pothole under the action of light traffic. Paige-Green and Netterberg (1987) discuss the functionality of unpaved roads in the public domain in terms of a similar set of defects as used in this analysis and their findings are summarised in Table 10.5. The variable of climate is omitted since the haul road functionality assessment is limited to a single climatic region as discussed in Chapter 3.

Table 10.4 Performance Properties of Natural Gravel Wearing Course Materials (after Mitchell, Petzer and van der Walt, 1979)

PERFORMANCE	LOWER LIQUID LIMIT	PLASTICITY INDEX	COARSE PLUS COARSE SAND CONTENT	PERCENTAGE CLAY
Corrugates	<20	-	>55	-
Dusty when dry	<20	-	<30	-
Ravels when dry	<20	<6	-	<6
Potholes when wet	>35	-	<30	-
Slippery when wet	-	>15	-	-
Cuts up when wet	-	-	<25	>10

Table 10.5 Material Properties Affecting Wearing Course Functionality (modified after Paige-Green and Netterberg, 1987)

MATERIAL PROPERTIES AFFECTING FUNCTIONALITY									
MATERIAL PROPERTY	SIGNIFICANT MATERIAL PROPERTY EFFECT ON DEFECT								
	POT	COR	RUT	LM	DST	STL	CRK	SKD	SKW
Boulder	X					X			X
Gravel	X			X				X	
Sand		X							
Silt				X	X		X		
Clay			X		X	X	X		X
Plasticity		X	X	X	X	X	X	X	X
Aggr strength	X					X		X	X
CBR	X	X	X						X

Traffic was also implicated as a significant variable in Paige-Green and Netterberg's work, all defect scores except dry skid resistance being related to traffic volume. From Table 10.5 it is evident that grading and plasticity are again the major factors that affect the functionality of wearing course materials. In this analysis, the wearing course material grading was represented by P132, P075, DR and GC independent variables, whilst PI, PL, LL and SP represent the principal measures of plasticity. Numerous other indirect material plasticity and grading inferences may be drawn from the remaining independent variables.

The rate of change in individual defect scores from the individual site and defect minimum or maximum has been determined for each defect described in Chapter 9.2 with the exception of the fixed stoniness defect since this parameter can be easily determined from sieve analysis results alone and it is unlikely that the fixed stoniness defect score can be predicted from, or is associated with, other material classification parameters.

In the following sections, the significant material property and other independent variables associated with a particular functional defect are discussed. Full statistics of the models and independent variables are presented in Table 10.6.

10.3.1 Potholing

The following model was developed to predict the rate of change of pothole defect score (LPOT) with days since last maintenance;

$$LPOT = 1{,}0998 - 0{,}001.D(4{,}138.LL + 1{,}462.KT + 0{,}567.SP) \qquad (10.5)$$

This model has an R-squared value of 66%, an F value of 40 which is significant at better than the 0,001% level for a sample size of 123. For the standard error of the model of 0,564 the approximate 95% confidence intervals for a rate of pothole defect score increase of 4 per unit time lie between 1,29 and 12,35. Plasticity was identified as an important material parameter in the formation of potholes (in terms of LL and SP), together with traffic volume. All the parameters included in the model reduce the pothole defect score from a maximum rate of increase of 3,00 per unit time. This maximum value occurs at time DM and the rate of defect score increase then reduces with time since last maintenance. The negative correlation of LL and SP with rate of increase of defect score indicates that pothole

Table 10.6 Individual Defect Score Progression Model Statistics and Associated Material Parameters

STATISTICS OF MODEL ESTIMATION FOR INDIVIDUAL ROAD DEFECTS								
	STATISTICS OF INDEPENDENT VARIABLES				RANGE OF VALUES			
MODEL	VARIABLE	STANDARD ERROR	t-VALUE	SIGNIF LEVEL OF t-VALUE	MEAN	STD. DEV	MIN	MAX
LPOT	Intercept	0,16715	6,58	0	-	-	-	-
	D.LL	0,0014	-3,97	0,0002	150,4	116,77	0	462
	D.KT	0,00075	-1,94	0,057	97,36	104,26	0	600
	D.SP	0,0002	-2,82	0,0064	864,86	635,31	0	2744
LCOR	Intercept	0,11515	6,87	0	-	-	-	-
	D.LL	0,00115	-8,62	0	150,4	116,77	0	462
	D.OMC	0,00195	5,53	0	57,2	62,65	0	315
	D.S	0,01094	-2,02	0,103	3,54	4,77	0	21
	D.M	0,01487	-2,17	0,03	3,46	5,48	0	21
LRUT	Intercept	0,1576	8,5	0	-	-	-	-
	D.KT	0,00073	-1,41	0,1	97,36	104,26	0	600
	D.GC	0,001	-6,97	0	194,44	144,44	0	550
	D.SP	0,00025	1,88	0,06	864,86	635,31	0	2744
-LLMM	Intercept	0,21295	6,58	0	-	-	-	-
	D.R	0,00033	-1,86	0,07	268,09	385,35	0	2040
	D.GC	0,00345	1,92	0,06	194,44	144,44	0	550
	D.LL	0,00401	-1,09	0,2	150,4	116,77	0	462
	D.DENS	0,00004	-3,13	0,003	14520,7	10492	0	39888
LLMF	Intercept	0,23077	8,77	0	-	-	-	-
	D.GC	0,00411	-5,07	0,0001	194,44	144,44	0	550
	D.LL	0,00691	4,5	0,0001	150,4	116,77	0	462
	D.SP	0,00043	-5,90	0	864,86	635,31	0	2744
LDST	Intercept	0,18394	9,77	0	-	-	-	-
	D.DR	0,0479	-9,19	0	3,65	2,66	0	11,7
LSTL	Intercept	0,1879	5,77	0	-	-	-	-
	D.DENS	0,00002	-7,33	0	14520,7	10492	0	39888
	D.KT	0,00017	2,76	0,007	97,36	104,26	0	600
	D.SP	0,00021	2,14	0,03	864,86	635,31	0	2744
	D.R	0,00024	-1,87	0,06	268,09	385,35	0	2040

Table 10.6 (continued) Individual Defect Score Progression Model Statistics and Associated Material Parameters

STATISTICS OF MODEL ESTIMATION FOR INDIVIDUAL ROAD DEFECTS								
	STATISTICS OF INDEPENDENT VARIABLES				RANGE OF VALUES			
MODEL	VARIABLE	STANDARD ERROR	t-VALUE	SIGNIF LEVEL OF t-VALUE	MEAN	STD. DEV	MIN	MAX
LCRL	D.DENS	0,00007	-2,02	0,05	14520,7	10492	0	39888
	D.LL	0,00521	1,53	0,14	150,4	116,77	0	462
	D.GC	0,0314	1,23	0,16	194,44	144,44	0	550
LCRS	Intercept	0,3317	3,66	0,0014	-	-	-	-
	D.KT	0,00538	-1,92	0,062	97,36	104,26	0	600
	D.R	0,00035	2,63	0,01	268,09	385,36	0	2040
	D.DENS	0,00002	-3,59	0,066	14520,0	10492	0	39888
LCRC	Intercept	0,18201	6,17	0	-	-	-	-
	D.LL	0,00107	-8,2	0	150,4	116,77	0	462
	D.M	0,02132	-2,27	0,027	3,46	5,48	0	21
-LSRD	Intercept	0,1424	12,74	0	-	-	-	-
	D.PL	0,00073	1,845	0,071	106,02	87,07	0	357
	D.DENS	0,00004	-3,71	0,0006	14520,7	10492	0	39888
	D.OMC	0,00394	-2,17	0,036	57,2	62,6	0	315
INFERENCE SPACE LIMITS FOR INDEPENDENT VARIABLES USED IN MODELS								
KT					20,88	16,20	6,0	50,0
DR					0,48	0,08	0,4	0,6
GC					28,4	4,29	21,3	36,3
CBR					73,96	23,54	46,0	132,0
SP					143,97	45,05	72,0	198,0
PI					6,56	1,78	4,0	10,0
R					47.45	44,22	0	141,0
LL					21,72	2,68	17,0	24,0
DENS					2161,73	161,74	1745,0	2343,0
OMC					7,65	2,6	5,2	15,0
PL					15,18	1,4	12,0	17,0
D					6,20	4,39	1,0	19,0

formation is associated with the ravelling of weakly cohesive materials as opposed to weak wearing course or subgrades. The negative correlation with traffic may be ascribed to associated maintenance activities (increased frequency of watering, etc) which reduce the severity of potholes, again supporting the concept of ravelling induced potholes as opposed to potholes formed due to material failure. However, the large confidence limits attached to the model suggest that secondary failure modes and other variables may contribute significantly to the defect score, particularly cracking, ponding of water and local structural failure. Figure 10.10 illustrates the correlation between predicted and actual pothole defect scores for all mine sites and Table 10.6 presents a statistical summary of the model parameters.

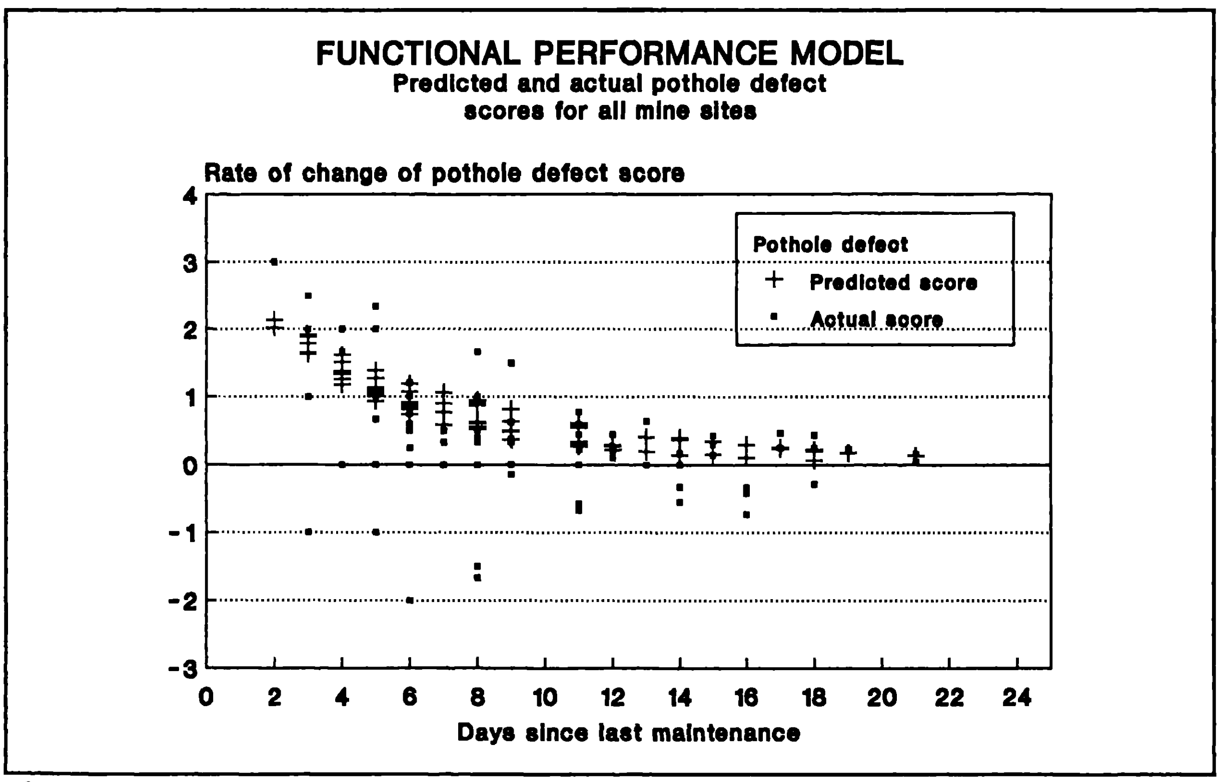


Figure 10.10 Comparison of predicted and actual pothole defect scores for all mine sites

10.3.2 Corrugation

The following model was developed to predict the rate of change of corrugation defect score (LCOR) with days since last maintenance;

$$LCOR = 0{,}7918 + 0{,}01.D(1{,}0781.OMC - 0{,}988.LL - 1{,}13.S - 3{,}227.M) \qquad (10.6)$$

This model has an R-squared value of 67% and an F value of 31 for a sample size of 128. For the standard error of the model of 0,41 the approximate 95% confidence intervals for a rate of corrugation defect score increase of 4 per unit time lie between 1,74 and 9,07. The material properties of LL and OMC confirm the characteristic established in Chapter 9.2.1.2 in which low plasticity materials with a high sand and silt content are more likely to corrugate. Equation [10.6] also reveals that corrugations are less severe in the wet season and that ferricretes are associated with a larger corrugation defect score than mixtures of material, all other factors being equal.

10.3.3 Rutting

The following model was developed to predict the rate of change of rutting defect score (LRUT) with days since last maintenance;

$$LRUT = 1{,}3405 - 0{,}001.D(1{,}039.KT + 6{,}981.GC + 0{,}462.SP) \qquad (10.7)$$

This model has an R-squared value of 60% and an F value of 49 for a sample size of 126. For the standard error of the model of 0,602 the approximate 95% confidence intervals for a rate of rutting defect score increase of 4 per unit time lie between 1,20 and 13,27. The significant material properties (at the 10% level or better) were that of grading (GC) and plasticity (SP) together with traffic volume, all three being negatively correlated with rate of change in defect score. The deformation of highly cohesive materials to form ruts under the action of traffic is not confirmed by this model and the inclusion of SP and GC (both negatively correlated) appears conflicting since an increase in GC represents a reduction in fines whilst an increase in SP an increase in either the fines content or linear shrinkage. No multi-collinearity was evident and as such rutting may be primarily associated with the ravelling and erosion of material in the wheel path, increasing cohesion slightly reducing the tendency of coarser graded gravels to ravel.

10.3.4 Loose Material

With reference to Figure 10.8, two modes of progression are evident for the loose material defect; a decreasing defect score with time (associated with mixtures of materials) and an increasing defect score with time (associated with ferricrete materials). Making the assumption of an exponential decrease or increase in rate of change of defect score, two models were developed, one for mixtures of materials (LLMM) and one for ferricretes (LLMF) as given below;

$$-LLMM = 1{,}4019 + 0{,}001.D(-0{,}628.R + 6{,}633.GC - 4{,}382.LL - 0{,}133.DENS) \quad (10.8)$$

$$LLMF = 2{,}0765 + 0{,}01.D(3{,}1169.LL - 2{,}056.GC - 0{,}255.SP) \quad (10.9)$$

Equation [10.8] has an R-squared value of 60% and an F value of 14 for a sample size of 73. For the standard error of the model of 0,505 the approximate 95% confidence intervals for a rate of loose material defect score decrease of 4 per unit time lie between 1,45 and 12,01. Equation [10.9] has an R-squared value of 70% and an F value of 31 for a sample size of 59. For the standard error of the model of 0,527 the approximate 95% confidence intervals for a rate of loose material defect score decrease of 4 per unit time lie between 1,41 and 11,42. The significant material properties affecting the formation of ravelling or loose material defect were (at the 20% level or better) material grading (GC) and plasticity (LL, SP and DENS), together with average monthly rainfall for mixtures of materials. For the ferricrete material model (LLMF) each property was negatively correlated with the dependent variable and no multi-collinearity was evident between the variables analysed. If ravelling is associated with a deficiency in cohesive components this is only partly confirmed by the model since an increase in GC effectively reduces the cohesive component of a wearing course.

10.3.5 Dustiness

The following model was developed to predict the rate of change of dustiness defect score (LDST) with days since last maintenance;

$$-LDST = 1{,}797 - 0{,}44067.D.DR \tag{10.10}$$

This model has an R-squared value of 73% and an F value of 84 for a sample size of 61. For the standard error of the model of 0,494 the approximate 95% confidence intervals for a rate of dustiness defect score decrease of 4 per unit time lie between 1,50 and 10,65. For the prediction of significant material properties the hypothesis of decreasing defect score with time was made as discussed previously, although the data presented in Appendix G2 suggests both increasing and decreasing rates of progression may be seen. The dust ratio (DR) material property is negatively correlated with the rate of defect score decrease which implies that an increase in DR serves to reduce the rate of decrease (i.e. the road is dustier). The inclusion of plasticity and seasonal factors were analysed but did not significantly improve the model. Figure 10.11 illustrates the correlation between actual and predicted dust defect scores for the assumed decrease in defect score with time.

10.3.6 Cracking

The following models were developed to predict the rate of change of longitudinal (LCRL), slip (LCRS) and crocodile (LCRC) cracking respectively;

$$LCRL = 0{,}001.D(7{,}971.LL - 0{,}146.DENS - 38{,}74.GC) \tag{10.11}$$

$$LCRS = 1{,}2158 + 0{,}01.D(0.0929.R + 1{,}034.KT - 0{,}0069.DENS) \tag{10.12}$$

$$LCRC = 1{,}1235 - 0{,}01.D(4{,}85.M - 0{,}887.LL) \tag{10.13}$$

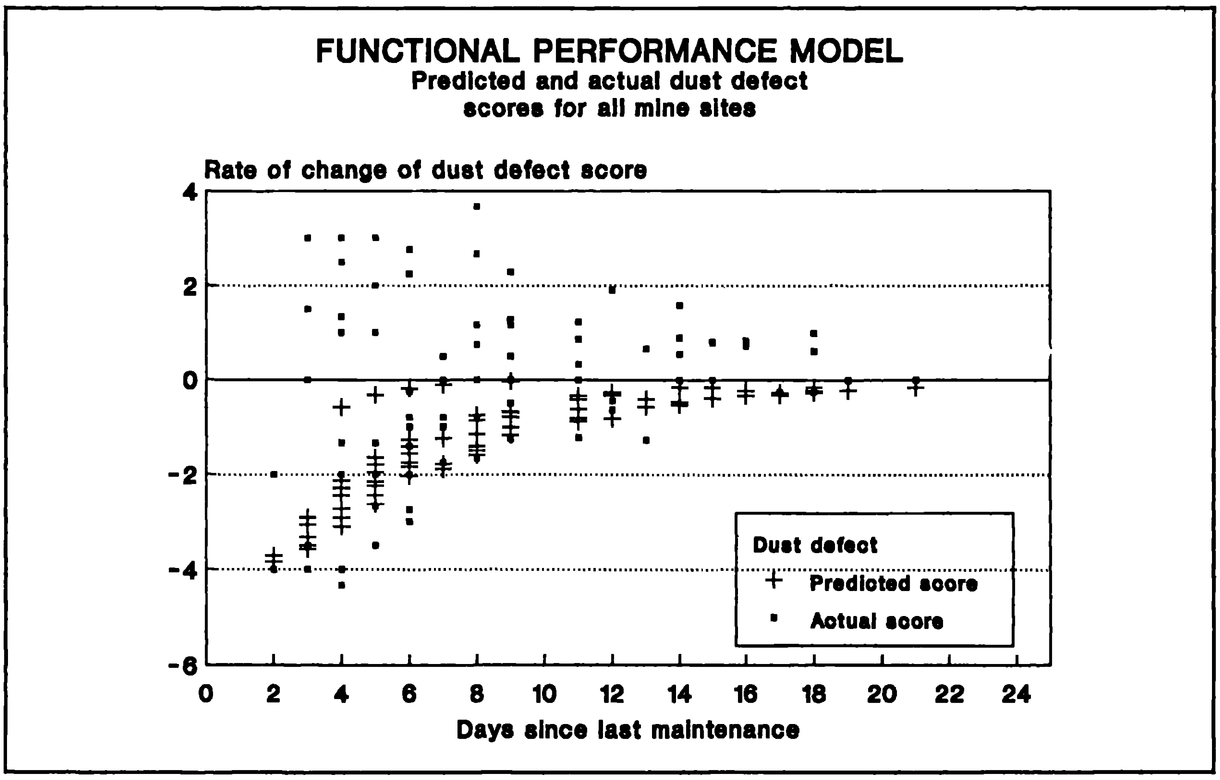


Figure 10.11 Comparison of predicted and actual dust defect scores for all mine sites (assuming decreasing defect scores with time)

Equations [10.11], [10.12] and [10.13] have R-squared values of 46%, 56% and 48% respectively and F values of 14, 11 and 16 for a sample size of 61. The standard errors of the models are high in comparison with the rates of defect scores increase, the approximate 95% confidence intervals for a rate of slip crack defect score decrease of 2 per unit time lie between 0,49 and 8,08. this may be compared to an average rate of approximately 0,8 per unit time. Of all the cracking defects analysed only crocodile cracking could be realistically associated with an exponential progression of rate of defect score increase with time, the other two cracking defects appearing to either remain static or increasing only very slightly with time. It is concluded that for slip cracks, the structural performance of the road exercises considerable influence over this defect as evidenced by the combined effects of rainfall and traffic volume. The material properties associated with crocodile cracking were found to be plasticity (LL and DENS) and gradation (GC). In general terms, factors such as temperature variation, wearing course and sub-grade stiffness and vehicle acceleration and deceleration are also important in assessing the tendency of a haul road to crack and their absence explains the relatively poor predictive capabilities of the models.

10.3.6 Wet and Dry Skid Resistance

The analysis of wet and dry skid resistance in terms of rate of change of defect score is illustrated in Figures 10.12 and 10.13 from which it may be seen that no single mode of progression is obvious. Both sites show a combination of decreasing and increasing rates of change. If the graph of wet skid resistance is analysed in terms of material grouping it is seen that when the five sites employing mixtures of materials are analysed (60 data points), 78% of these points show either increasing or decreasing rates whilst those sites using ferricrete materials (six sites, 72 data points) remain essentially static (85% exhibiting a zero rate of change). It is concluded that mixtures of wearing course materials are thus likely to exhibit more changeable wet skid resistance defect scores than ferricrete materials.

In terms of dry skid resistance if loose material is assumed to be associated with dry skid resistance, a decrease in defect scores with time could be adopted. Analysis of the data reveals such an assumption omits 39% of the data. Accepting this omission and analysing the remaining data gave the following model;

$$-LSRD = 1{,}8158 + 0{,}01.D(1{,}346.PL - 0{,}0157.DENS - 0{,}853.OMC) \qquad (10.14)$$

This model has an R-squared value of 82% and an F value of 65 for a sample size of 81. For the standard error of the model of 0,394 the approximate 95% confidence intervals for a rate of dry skid resistance defect score decrease of 4 per unit time lie between 1,81 and 8,67. Material properties associated with plasticity were all found to be significant at the 6% level or better. A material which is not prone to the production of excessive loose material or ravelling will exhibit improved dry skid resistance, especially in the presence of high plasticity (cohesion). The identical conditions will, however, in the wet state, lead to a reduction in wet skid resistance. In the selection of appropriate material selection guidelines cognisance should thus be taken of operators preference in terms of wet or dry skid resistance problems. The low plasticity index values attributable to the various groups of materials currently in use on the mines suggests preference is given to reducing any wet skid resistance defects to the detriment of (less problematic) dry skid resistance, loose material, ravelling and corrugation defects.

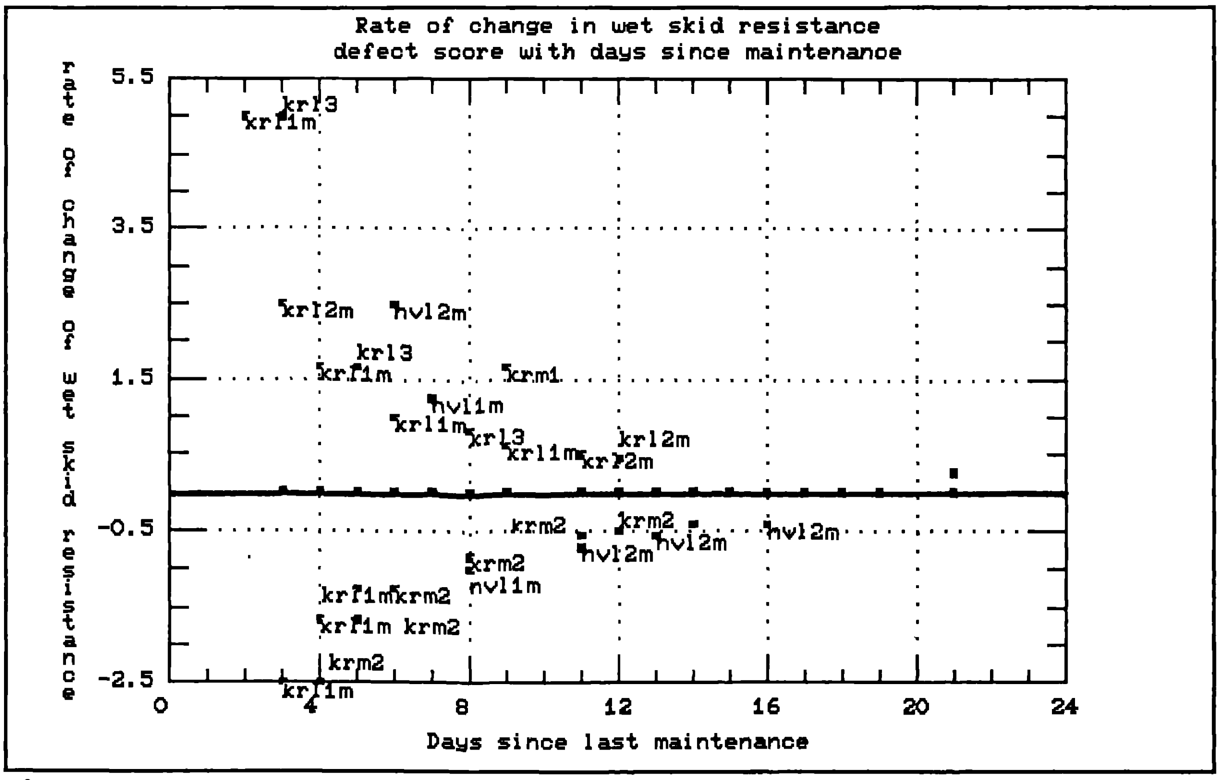


Figure 10.12 Rate of change of wet skid resistance defect score with days since last maintenance.

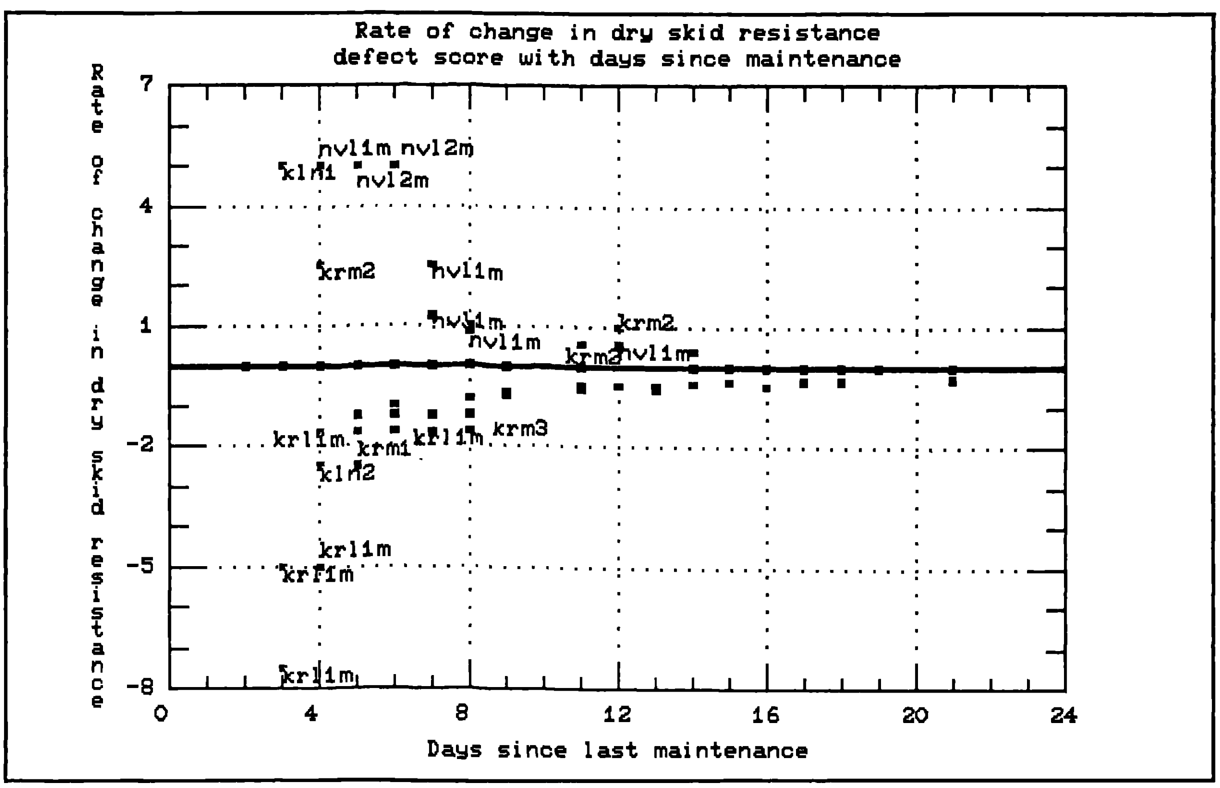


Figure 10.13 Rate of change of dry skid resistance defect score with days since last maintenance.

10.4 Summary and Conclusions

This chapter concerned the statistical analysis of deterioration and maintenance effects and the development of a predictive model for defect score progression between maintenance cycles, together with a statistical analysis of wearing course material parameters and individual defect scores to determine parameters implicated in each type of haul road defect.

The defect progression model was derived from consideration of the rate of change in overall defect score over a maintenance cycle, in terms of the decrease and then increase in defect scores, together with an assessment of the location of the minimum defect score time-wise. The model incorporated wearing course material properties, especially grading and plasticity parameters, together with traffic volume. The high prediction errors associated with the model are ascribed to the variability in both the defined and undefined independent variables which control defect progression rates. The applicability of the model is limited by the relatively small inference space of the data and where materials are encountered which differ significantly from those assessed during the test work the results would not be valid. Nevertheless, the model provides a suitable base for the further development of a maintenance and design system model and as a measure of likely pavement condition at the minimum cost solution to the maintenance management system model.

Whilst a model of defect score progression is useful to predict and compare the functional performance of a particular wearing course material (in terms of its engineering properties and the traffic volume on the road) with the acceptability requirements of the road-user it is

also necessary to determine the propensity of a particular material to form specific functional defects, also through consideration of material engineering properties and the rate of change in defect score associated with the road test section. The emphasis with this analysis was the identification of material parameters as opposed to the prediction of defect scores from material property parameters.

By analysing the rate of defect score change beyond the minimum value encountered, models were developed using the hypotheses of either increasing or decreasing rates of change. By using a transformation to linearise the data the additional assumption of approximately exponential rates of increase or decrease could be incorporated, in keeping with the similar assumption for overall defect score progression rates. From the analysis it was found that in general, the grading of the wearing course material together with plasticity influence functional performance significantly. In determining suitable wearing course material selection guidelines the work in this chapter confirms that grading and plasticity parameters will adequately anticipate the functional performance of the materials thus far assessed. From the regression analysis it is clear that other unquantified factors are significant in the individual defect score progression and particular defects may be inter-related.

Once road-user acceptability limits for each defect are determined, the corresponding limits for the significant material parameters implicated in each defect may be resolved through consideration of the individual defect score models and the ranking of defects in terms of safety and operational impact. These acceptability limits are discussed in the following Chapter prior to the derivation of material property limits.

CHAPTER 11
ACCEPTABILITY CRITERIA FOR HAUL ROAD FUNCTIONAL PERFORMANCE

11.1 Introduction

From the analysis and quantification of mine haul road functional performance presented in Chapters 9 and 10, various levels of performance were established for a range of wearing course material types and traffic volumes, together with an indication of those material properties that are significantly correlated with a particular functional defect. This information cannot be used to assess the applicability of current material selection guidelines for unpaved road construction without some measure of acceptability limits for the various material, formation and functional defects previously analysed. This chapter introduces the methodology adopted in determining acceptability limits for mine haul road functionality, following which the results are analysed and acceptability limits deduced as a precursor to the assessment of established selection guidelines when applied to mine haul road functional design.

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 selecting alternative wearing course materials 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 estimate the functionality of a wearing course material. As a first step in addressing this problem, a survey was made of participating mines to determine what levels of functionality are required from a wearing course material.

In addition to defining acceptability limits, the data generated during the analysis was also used to indicate the accident potential associated with each type of haul road defect. These results are important both from the point of view of maintenance design and management and as a vindication of the relative importance attached to each defect in the final selection guidelines established for mine haul roads.

11.2 Acceptability Criteria for Haul Roads

Criteria defining the acceptability of paved roads are widely available and have been summarised by Visser (1981). For unpaved roads, acceptability criteria generally involved a subjective assessment of one particular measure of functional performance. Visser (1981) introduced the concept of limiting conditions, representing the minimum conditions that need to exist for the road to fulfil its functionality requirements. In this assessment of acceptability, each of the previously identified wearing course defects are assessed in terms of desirable, undesirable and unacceptable limits of performance.

In order to quantify these parameters each participating mine was invited to complete a functionality rating questionnaire in which both production and engineering personnel had inputs. To further quantify the limits of acceptability respondents were also invited to categorise each defect in terms of its impact on the components of the hauling system, namely the truck, tyres or operation. In addition, haul truck manufacturers were also invited to respond so as to qualify mine operators functionality requirements with those of the manufacturers.

11.2.1 Functionality Questionnaire

The series of questions and evaluations contained in the questionnaire were designed to assess the functional performance of a haul road both in terms of acceptable functional performance levels and the effect of performance deficiencies on a truck, its tyres and the productivity of the whole transport operation. Respondents were asked to reply to the questions using their overall familiarity with surface mining, together with their perceptions about haul road functionality and the relationship between the haulage system and safe and economic mining operations.

Two basic areas were evaluated by the questionnaire;

1 Road user assessment of desirable and unacceptable characteristic performance limits and
2 The impact of functionality on the economics and safety of the operation.

The first area was assessed by using the standard descriptions of degree and extent for each wearing course, formation and function defect referred to in Chapter 9.2.1. Respondents classified the lower limit of desirability and the upper limit of unacceptability for each defect.

The second area was quantified using an approach developed by United States Bureau of Mines Minerals Health and Safety Technology Division (USBM, 1981), suitably modified to accommodate those conditions or characteristics previously identified as important in the functional performance of wearing course materials. Respondents were asked initially to decide if a given condition or characteristic can affect either the truck, the tyres or the operation's productivity. If any of these three items are affected, the degree to which this occurs was scored using the rating system given in Table 11.1. The safety impact was estimated by scoring the accident potential of each condition and characteristic. Accident potential assigns a subjective probability to every condition and characteristic as given in Table 11.2. An accident in this case is defined as an unplanned event which results in operator injury or equipment damage. Respondents were asked to consider each item in a broad sense, ie., scoring in terms of its impact on average or typical daily operating conditions on the haul road.

The questionnaire is presented in Appendix H together with the instructions to respondents. Details of the methodology used to compile the results are given in the following sub-sections.

Table 11.1 Impact Ranking Scale (following USBM, 1981)

ITEM	IMPACT SCORE	DESCRIPTION
TRUCK		
	0	No mechanical damage
	1	Minor mechanical damage, downtime < 1 shift, low potential for premature component failure.
	2	Minor mechanical damage, downtime < 1 shift, medium potential for premature component failure.
	3	Mechanical damage, downtime < 1 week, high potential for premature component failure.
	4	Mechanical damage, downtime < 1 month.
	5	Mechanical damage, downtime > 1 month.
OPERATION		
	0	< 1% slow down.
	1	1-5% slow down.
	2	6-10% slow down.
	3	11-15% slow down.
	4	>15% slow down.
	5	Production stops.
TYRES		
	0	No impact on tyre wear.
	1	Tyre wear increased by 5%.
	2	Tyre wear increased by 10%, low potential for cuts.
	3	Tyre wear increased by 25%, medium potential for cuts.
	4	Tyre wear increased by 50%, high potential for cuts.
	5	Tyre wear increased by >50%, high potential for cuts.

11.2.2 Road User Assessment of Functional Performance Limits

The functionality questionnaire was sent to all AMCOAL strip coal mines participating in the research project and responses were received from both mining production and engineering personnel. In addition, the response of haul truck manufacturers was also sought so as to

Table 11.2 Accident Potential (following USBM, 1981)

ACCIDENT POTENTIAL SCORE	DESCRIPTION
0	Could cause an accident resulting in operator injury or equipment damage but probability is low (P<1%).
1	P 1-5%
2	P 6-10%
3	P 11-20%
4	P 21-30%
5	P 31-42%
6	P 43-54%
7	P 55-66%
8	P 67-78%
9	P 79-90%
10	Very high probability of accident. If situation is left uncorrected, accident involving equipment damage or operator injury will almost certainly occur (P>90%)

highlight any misconceptions between the road performance considered acceptable by mine personnel and that considered acceptable by the manufacturers. In total 13 completed questionnaires were received, 10 from mine personnel and 3 from truck manufacturers. The sample size is small, but in terms of years of operating experience with mine haul roads, they represent 107 and 62 years respectively. In addition, the data is representative of nearly 70% of the total coal tonnage transported on mine haul roads in South Africa. With regard to manufacturer data, the 3 respondents represent all the haul truck suppliers to the coal strip mines.

Acceptability criteria for each type of defect assessed were analysed in terms of the average scoring of degree and extent of each defect, categorised according to either acceptable (equal to or less than a particular score) or unacceptable (equal to or greater than a particular score) performance. From this data, three categories of performance are deduced as given in Table 11.3. For the defects of skid resistance (wet and dry) and drainage (road and road side) an extent of 5 is assigned.

Table 11.3 Categorisation of Functional Performance Limits

PERFORMANCE CLASSIFICATION	EQUIVALENT PERFORMANCE CLASSIFICATION FROM QUESTIONNAIRE
Desirable (1)	Product of defect Degree x Extent less than or equal to average acceptable
Undesirable (2)	Product of defect Degree x Extent between desirable and unacceptable
Unacceptable (3)	Product of defect Degree x Extent greater than or equal to average undesirable

Table 11.4 presents a summary of the responses in terms of average degree and extent scores for each defect, together with the average acceptability limits derived therefrom. Figure 11.1 presents the information graphically. Using the criteria given in Table 11.3, functional performance limits may be identified for each defect as shown in Figure 11.2. From these figures it is evident that potholes, corrugations, loose material, dustiness, loose stones and wet and dry skid resistance are considered undesirable when degree of the defect exceeds 1,5-1,8 (for skid resistance wet and dry the assumed extent of 5, representing conditions affecting the whole road, artificially exaggerates the lower limit of desirability). Cracking was not seen as a serious defect in terms of the acceptability limits, crocodile cracks being assigned a lower limit of degree 2,5. This indicates that there may be insufficient recognition of the significance of cracking as a precursor to more serious secondary defects.

Using the acceptability limits for each defect illustrated in Figure 11.2, the performance of each mine test site can be quantified in terms of the range and average of the defect score over the assessment period. A typical test site performance in relation to the established limits is given in Figure 11.3, derived from data presented in Chapter 9 and Appendix F4. Full results are given in Appendix H and a summary presented in Table 11.5 for all mine test sites. These results will be analysed further in Chapter 12 where they form the basic criteria used to evaluate wearing course selection criteria.

Table 11.4 Limits of acceptability for functional performance

SUMMARY OF FUNCTIONAL QUESTIONNAIRE RESPONSES Limits of acceptability for functional performance according to performance classification (Table 11.3)						
Defect	Acceptable defect scores		Unacceptable defect scores			
	Average Degree (less than)	Average Extent (less than)	Average Degree (greater than)	Average Extent (greater than)	Average Desirable degree x extent (less than)	Average Uncceptable degree x extent (greater than)
Potholes	1.5	2.1	3.1	3.3	3.2	10.2
Corrugations	1.5	2.3	2.8	3.5	3.4	9.9
Rutting	2.1	2.4	3.2	3.2	5.0	10.2
Loose material	1.5	2.4	2.9	3.1	3.5	9.0
Dustiness	1.5	2.5	3.3	3.3	3.9	10.9
Stoniness - fixed	1.8	2.4	3.4	3.2	4.4	10.9
Stoniness - loose	1.5	1.9	2.9	2.9	2.8	8.5
Cracks - longitudinal	2.2	2.3	3.4	3.3	5.0	11.2
Cracks - slip	2.3	2.5	3.7	3.5	5.7	13.1
Cracks - crocodile	2.5	2.5	3.8	3.5	6.2	13.3
Skid resistance wet	1.8		2.9		8.8	14.6
Skid resistance dry	1.8		2.9		8.8	14.6
Drainage on road	1.6		3.2		8.1	15.8
Drainage side of road	1.5		3.0		7.7	15.0

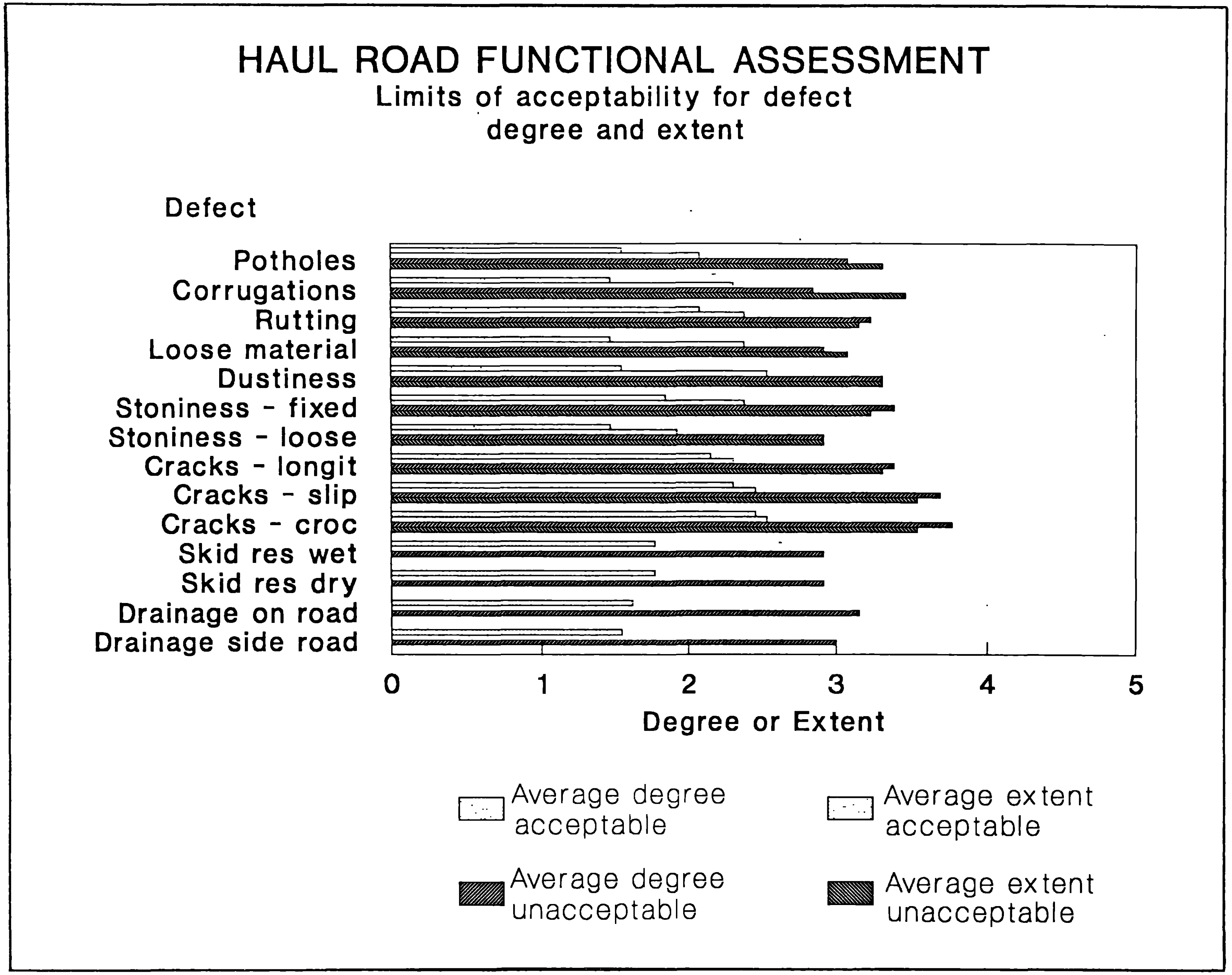


Figure 11.1 Limits of Acceptability for Defect Degree and Extent

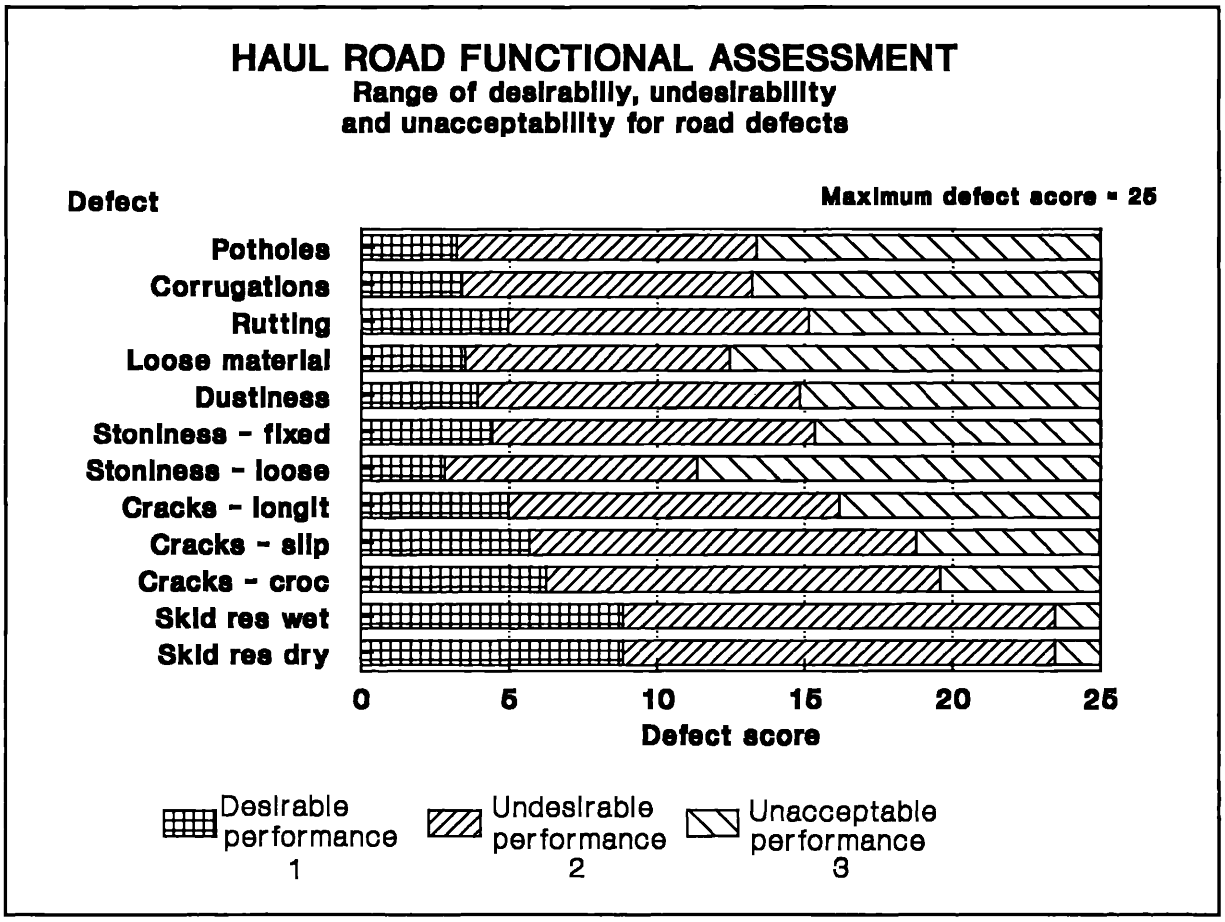


Figure 11.2 Limits of Defect Functional Performance

Whilst establishing the acceptability limits for each functional defect provides an insight into the ideal levels of performance expected for a wearing course material, an appraisal of the impact of these defects on the hauling operation is necessary to qualify the extent to which defects may affect economics and safety.

11.2.3 Road User Assessment of Defect Impact

The impact of a particular functional defect is quantified on the questionnaire using the impact ranking scale which reflects that common functional defects, resulting from a less than optimal wearing course material (or maintenance program) are not catastrophic. Results were compiled for average annual functionality of a mine's road. The methodology adopted in analysing the results involved determining the percentage of respondents identifying a

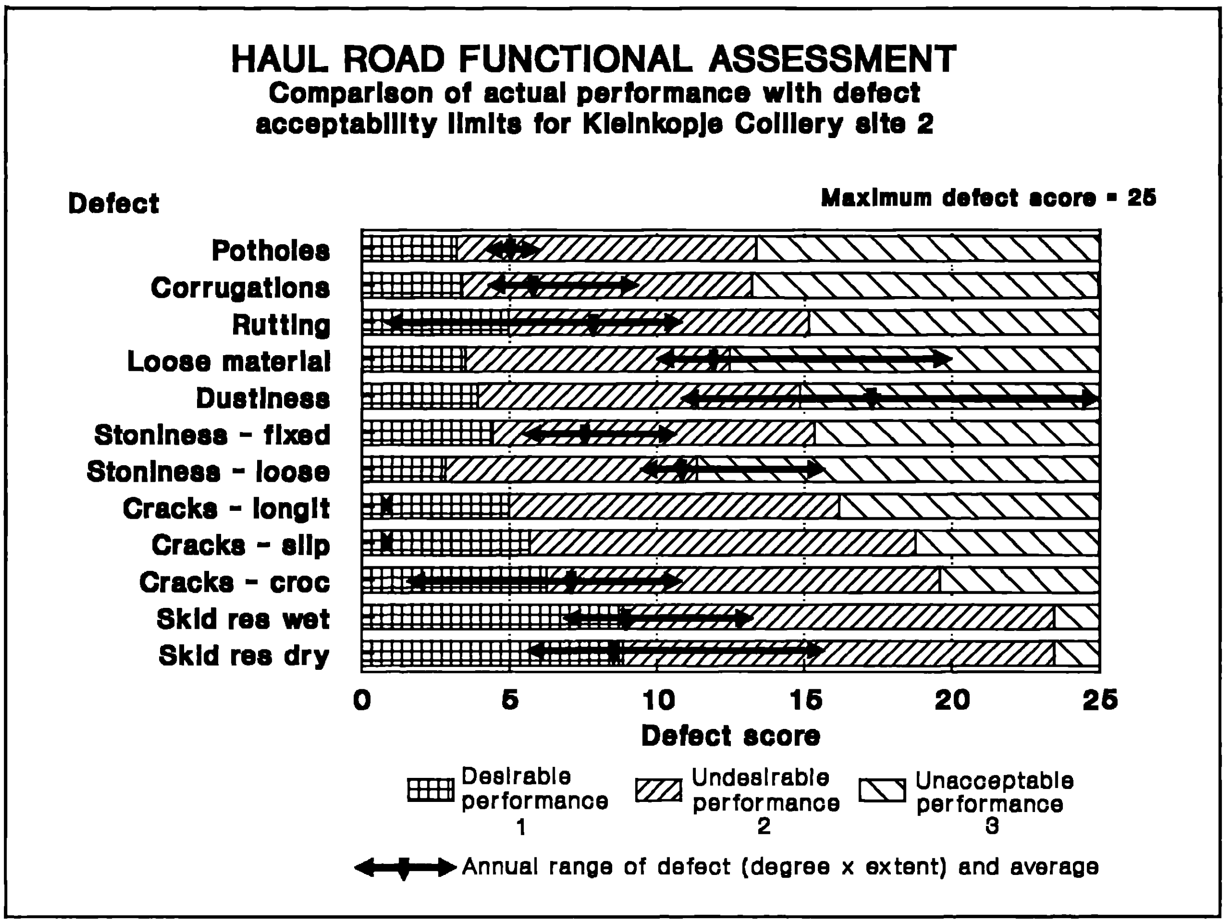


Figure 11.3 Range and Annual Average Values for Mine Test Site Functional Performance in Relation to Established Performance Limits.

particular defect with each of three components of hauling; the operation itself, the truck and its tyres. Average impact scores are also determined for each component and finally the weighted impact calculated as the product of the percent respondents identifying the impact and its average impact score. Table 11.6 gives the results of the analysis and Figure 11.4 shows the impact of each particular defect on operation, truck and tyre. These results echo the road user assessment of functionality with dustiness and wet skid resistance perceived as being primary defects affecting the operation, accounting each for an 11-15% reduction in productivity. Impacts on the truck centred on the defects of potholes, corrugations and skid resistance, accounting for downtimes of less than one shift. Impacts on the tyre were similar, including in addition loose material and stoniness, accounting for a 5-10% decrease in tyre life. Cracks were considered almost irrelevant in terms of their impact on the hauling components.

Table 11.5 Summary of Mine Haul Road Test Site Performance in Relation to Established Performance Criteria.

FUNCTIONAL PERFORMANCE CLASSIFICATION OF MINE TEST SITES											
DEFECT	KRIEL COLLIERY			KROMDRAAI COLLIERY			NEW VAAL COLLIERY			KLEINKOPJE COLLIERY	
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2
Potholes	2	2	2	2	1	2	2	1-2	2	2	2
Corrugations	2	2	2	1-2	1-2	1	2	1-2	2	2	2
Rutting	2	3	2	1-2	1-2	1	1-2	1-2	2	2	2
Loose material	2-3	2	2	2	2	2	2	2	3	2-3	2-3
Dustiness	2-3	2	2	2	2-3	2	2	2-3	3	3	3
Stoniness - fixed	2	2	2	1-2	1	2	2	2	2	2	2
Stoniness - loose	2	2	2	2	2	1	2	2	2	2	2-3
Cracks - longitudinal	1	1	1	1	1	1	1	1	1	1	1
Cracks - slip	1	2	1	1	1	1	2	1	1	1	1
Cracks - crocodile	2	2	1	1	1	1	2	1	1	1	2
Skid resistance - wet	2	3	2	1	2	2	2	2	2	2	2
Skid resistance - dry	2	2	2	1-2	2	2	2	2	2	2	1-2

Key

1 Desirable performance

2 Undesirable performance

3 Unacceptable performance

Table 11.6 Summary of Defect Impact and Accident Potential

SUMMARY OF FUNCTIONAL QUESTIONNAIRE RESPONSES

Impact of functionality on safety

Defect	Percent responses identifying defect impact			Average defect impact score			Weighted defect impact score (percent respondents identifying impact x average score/100)			Percent responses identifying defect accident potential	Average defect accident potential	Weighted average defect accident potential
	Operation	Truck	Tyres	Operation	Truck	Tyres	Operation	Truck	Tyres			
Potholes	100.0	92.3	100.0	2.1	1.7	1.3	2.1	1.5	1.3	100.0	1.4	1.4
Corrugations	100.0	92.3	92.3	2.2	2.1	1.9	2.2	1.9	1.7	100.0	1.5	1.5
Rutting	92.3	61.5	76.9	1.8	1.9	1.3	1.7	1.2	1.0	84.6	1.5	1.2
Loose material	84.6	46.2	76.9	2.3	0.5	2.0	1.9	0.2	1.5	92.3	2.9	2.7
Dustiness	100.0	53.8	15.4	3.2	1.1	1.5	3.2	0.6	0.2	92.3	5.5	5.1
Stoniness - fixed	61.5	46.2	92.3	2.4	1.5	1.9	1.5	0.7	1.7	84.6	1.4	1.2
Stoniness - loose	84.6	53.8	92.3	2.2	0.9	1.8	1.8	0.5	1.6	92.3	2.1	1.9
Cracks - longitudinal	23.1	30.8	53.8	1.7	1.5	1.5	0.4	0.5	0.8	61.5	0.9	0.5
Cracks - slip	23.1	38.5	53.8	1.7	2.4	1.8	0.4	0.9	1.0	61.5	1.5	0.9
Cracks - crocodile	30.8	23.1	53.8	1.5	1.7	1.5	0.5	0.4	0.8	61.5	1.3	0.8
Skid resistance wet	100.0	46.2	69.2	3.3	3.2	2.2	3.3	1.5	1.5	92.3	4.6	4.2
Skid resistance dry	92.3	46.2	69.2	2.4	3.2	2.4	2.2	1.5	1.7	92.3	3.8	3.5
Drainage on road	100.0	23.1	76.9	2.5	0.7	2.3	2.5	0.2	1.8	92.3	2.5	2.3
Drainage side of road	100.0	38.5	61.5	1.9	1.2	1.8	1.9	0.5	1.1	100.0	3.0	3.0

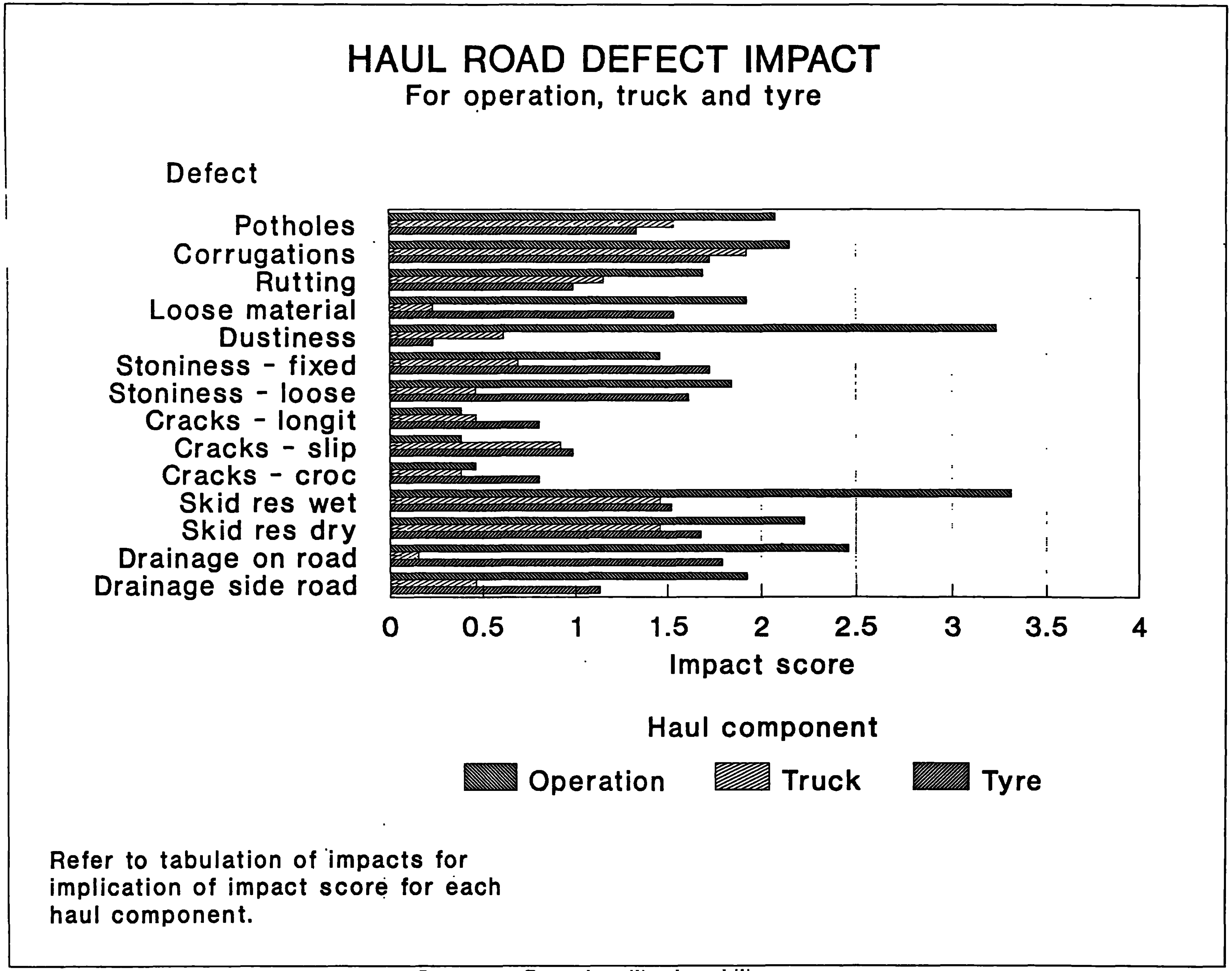


Figure 11.4 Haul Road Functional Defect Impact on Operation, Truck and Tyre.

The accident potential was determined in a similar fashion, in this case irrespective of which component of the hauling it affects. The accident potential scale assigns probabilities that the impact will occur. The weighted average accident potential scores are given in Table 11.6 and shown graphically in Figure 11.5 from which it is seen that the defects of dust and skid resistance are the functional factors most likely (probability between 40% and 50%) to cause accidents. The formational defect associated with drainage on the side of the road was recognised as having a high accident potential (probability of upto 30%) which also implicates the functional defect of loose material or in more general terms, wearing course

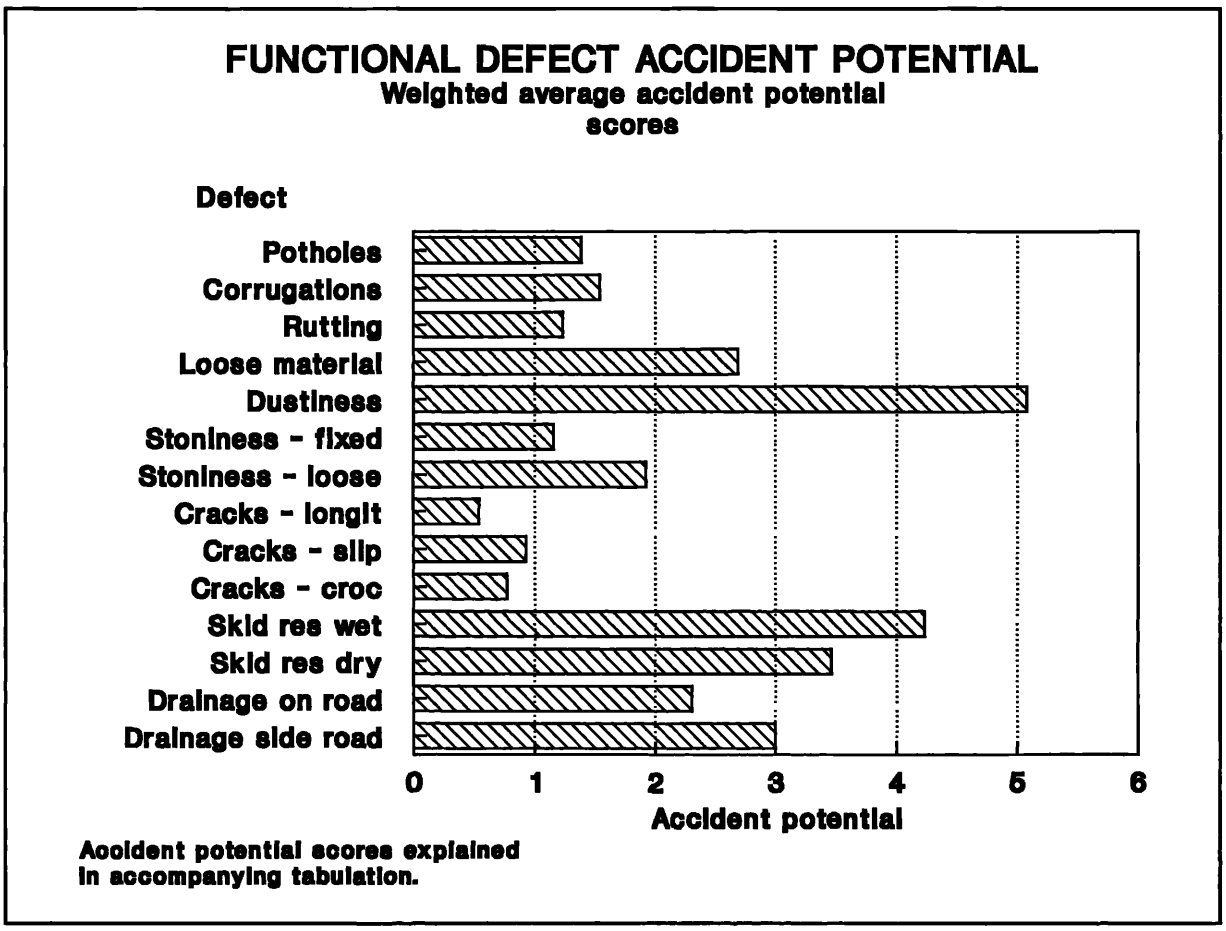


Figure 11.5 Accident Potential of Haul Road Functional Defects.

material erodibility, in accidents. Material loss was not considered as a variable in the development of wearing course material selection guidelines since it is a long term parameter (Paige-Green, 1989) and on mine haul roads, wearing course material is often bladed off the road during wet weather and returned once the material has dried.

11.3 Defect Ranking System

From the foregoing analysis of defect impact and accident potential a combined defect ranking system can be derived to assist in identifying and categorising aspects of functional performance that should enjoy priority when considering opposing selection criteria. The ideal characteristics for wearing course materials were initially considered in terms of public unpaved road criteria as outlined in Chapter 2.3.2. It was concluded that those characteristics provide a good starting point, but may require modification in the light of the disparate functional requirements of haul road users.

The methodology for ranking defect involves summing the product of component impact and accident potential for each defect to give a cumulative defect score for each defect. The product of cumulative impact score, cumulative defect score and accident potential then gives the overall ranking of the defect. Table 11.7 shows the results of the ranking whilst Figure 11.6 shows the actual ranking scores. It is evident that wet skid resistance has the greatest impact and accident potential, followed by dust, dry skid resistance and loose material. The formational aspects of drainage, both on and off the road are also significant in the ranking of functional defects.

The data generated by the questionnaire, both in terms of defect impact and ranking can also be used as a basis for an analysis of the Rand cost of operational inefficiencies associated with haul road defects. This aspect will be fully addressed in the work on maintenance management systems for mine haul roads.

11.4 Conclusions

The development of acceptability criteria for haul road functionality fulfils a deficiency identified in the literature review. Each functional defect has been ascribed a range of scores in terms of degree and extent covering desirable, undesirable and unacceptable performance. This will enable a comparison to be made between the functionality of the various types of wearing course material surveyed prior to establishing the suitability of existing wearing

Table 11.7 Ranking of Haul Road Defects.

FUNCTIONAL DEFECT RANKING							
Defect	Weighted impact score for component			Cumulative component impact score	Average accident potential	Cumulative defect score	Defect Ranking
	Operation	Truck	Tyres				
Potholes	2.1	1.5	1.3	4.95	1.4	6.85	46.95
Corrugations	2.2	1.9	1.7	5.81	1.5	8.93	79.83
Rutting	1.7	1.2	1.0	3.84	1.5	5.58	31.12
Loose material	1.9	0.2	1.5	3.69	2.9	10.77	115.98
Dustiness	3.2	0.6	0.2	4.08	5.5	22.42	502.79
Stoniness - fixed	1.5	0.7	1.7	3.88	1.4	5.30	28.06
Stoniness - loose	1.8	0.5	1.6	3.92	2.1	8.17	66.80
Cracks - longit	0.4	0.5	0.8	1.65	0.9	1.45	2.09
Cracks - slip	0.4	0.9	1.0	2.29	1.5	3.44	11.85
Cracks - croc	0.5	0.4	0.8	1.65	1.3	2.07	4.27
Skid res wet	3.3	1.5	1.5	6.29	4.6	28.84	831.73
Skid res dry	2.2	1.5	1.7	5.37	3.8	20.15	406.07
Drainage on road	2.5	0.2	1.8	4.41	2.5	11.03	121.56
Drainage side of road	1.9	0.5	1.1	3.51	3.0	10.54	111.06

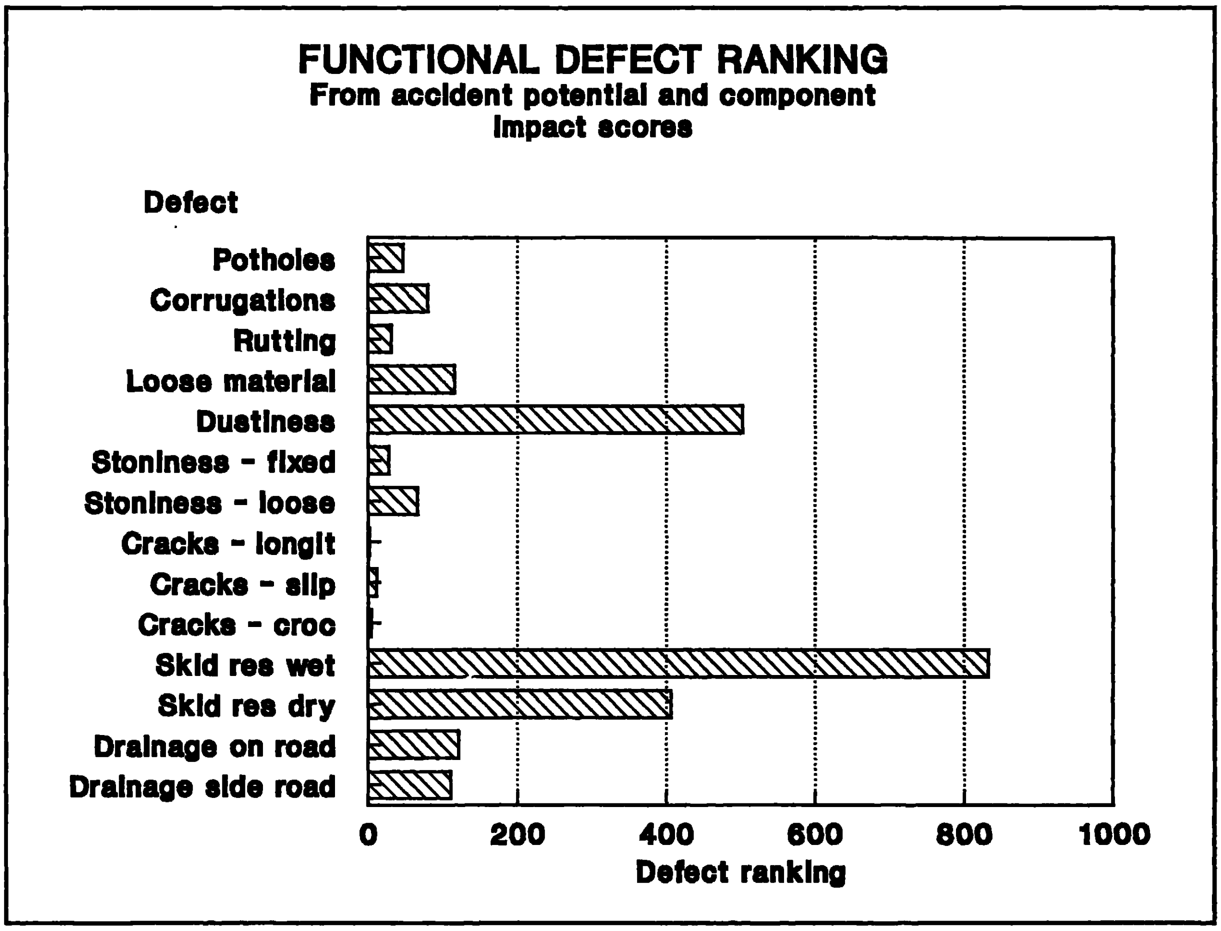


Figure 11.6 Ranking of Haul Road Defects

material selection guidelines for haul road construction.

A total of 13 mine or truck manufacturing personnel responded to the questionnaire. Although a small sample it is believed that the results are valid in terms of total coal tonnage transported on strip coal mine roads. The results represent nearly 70% of the total strip mine tonnage hauled in 1995, equivalent to 1,056 million annual haul truck-trips. Further justification for accepting this small sample size is based on the close agreement seen between the data. It may be anticipated that further sampling would generate very similar results as to those already analysed.

In addition to assigning acceptability ranges to each type of defect, the impact and accident potential of each defect has been categorised and ranked according to the total impact and accident potential on the components of hauling, namely operation, truck and tyre. It is concluded from the ranking exercise that skid resistance (wet), dustiness, erodibility and ravelling and corrugating are critical defects which control the functionality of mine haul roads. These defects should therefore either be present or incorporated into any suitable selection criteria established for mine haul road wearing course materials.

CHAPTER 12

DERIVATION OF WEARING COURSE MATERIAL SPECIFICATIONS

12.1 Introduction

The derivation of wearing course material selection guidelines is based on the identification, characterisation and ranking of haul road functional defects as discussed in the previous chapters. Prior to the development of the specifications a reference framework was developed within which suitable specifications should fall. This was based on an assessment of the requirements of good specifications in the light of the functional defect ranking and acceptability limits derived in Chapter 11.

Two approaches were adopted in deriving suitable specifications. Initially, the important material property parameters controlling both functional performance and individual defect score progression rates were assessed in relation to the overall haul road functional performance classification in order to identify likely trends and limits for individual parameter values. Secondly, the suitability of the wearing course material selection guidelines proposed in TRH20 (CSRA, 1990) as a source for mine haul road material specification were analysed. This enabled specifications to be developed which, whilst stipulating individual parameter limits also have predictive capabilities which contribute to an understanding of the consequences when materials outside the specified ranges are used as wearing course materials.

12.2 Specification Requirements

The development of suitable specifications for wearing course materials should ideally encompass both individual wearing course material parameter specification and a broader indication of likely functional defects associated with departure from the established guidelines. Paige-Green (1989) described ideal specification requirements from the point of view of public unpaved roads and these are presented overleaf, modified in terms of mine haul road design and operation.

(i) They should be simple with as few requirements or test methods as possible.

(ii) They should be inexpensive, reproducible, necessitate the minimum of sophisticated equipment and operator training.

(iii) The limits should not be restricted to a narrow range of a significant property, but must also be adequately comprehensive in order to recognise and reject unsuitable materials.

(iv) The specifications should not be unduly restrictive and accommodate mine haul road construction cost and material volume considerations. An indication of the likely consequences of employing local mine material which falls outside the recommended parameter range is useful.

Material selection guidelines must thus take cognisance of the road-user functional performance requirements and the limitations imposed by material availability, cost and volume considerations. Since some defect/material property trade-off is inevitable when local mine construction materials are used it is important to establish a performance ranking system in which material properties associated with critical defects enjoy priority over less significant defects, especially where opposing material selection parameters are encountered.

12.2.1 Performance Ranking

In the road-user assessment of defect acceptability criteria presented in Chapter 5, a haul road functional performance ranking was developed in terms of functional defect impact on truck, tyre, operation and safety. A number of defects which critically affect functionality were identified and considered to represent the critical defects which should be addressed in the derivation of material specifications. Limits of acceptability were also determined in terms of desirable, undesirable and unacceptable levels of defect score. These acceptability limits are categorised in Table 12.1 whilst in Table 12.2 the corresponding desirable and unacceptable limits are given for each critical defect analysed.

The acceptability limits of desirable, undesirable and unacceptable, derived from user defined acceptability criteria appear unnecessarily restrictive when each test site or critical defect is

Table 12.1 Categorisation of Functional Performance Limits

PERFORMANCE CLASSIFICATION	EQUIVALENT PERFORMANCE CLASSIFICATION FROM QUESTIONNAIRE
Desirable (A)	Product of defect *Degree x Extent* less than or equal to average road user defined acceptable score
Undesirable (B)	Product of defect *Degree x Extent* between desirable and unacceptable
Unacceptable (C)	Product of defect *Degree x Extent* greater than or equal to average road user defined unacceptable score

Table 12.2 Performance Ranking and Acceptability Limits for Critical Functional Defects.

CRITICAL DEFECT ACCEPTABILITY LIMITS		
	Acceptability limits (based on a maximum defect score of 25)	
Defect	**Desirable** (less than)	**Unacceptable** (greater than)
Corrugation	3	10
Loose material	3	9
Dustiness	4	11
Loose stoniness	3	9
Wet skid resistance	3	15[1]
Dry skid resistance	3	15[1]
NOTES 1. Using an assumed maximum extent score of 5.		

classified according to these three groupings; those mine sites exhibiting a reasonable level of functional performance were not adequately differentiated from noticeably poorer sites. A further sub-division of performance classification was developed in order to adequately differentiate between these sites and defects. The performance classifications of undesirable and unacceptable were thus subdivided into upper (B1 and C1) and lower (B2 and C2) sub-groups as shown in Figure 12.1

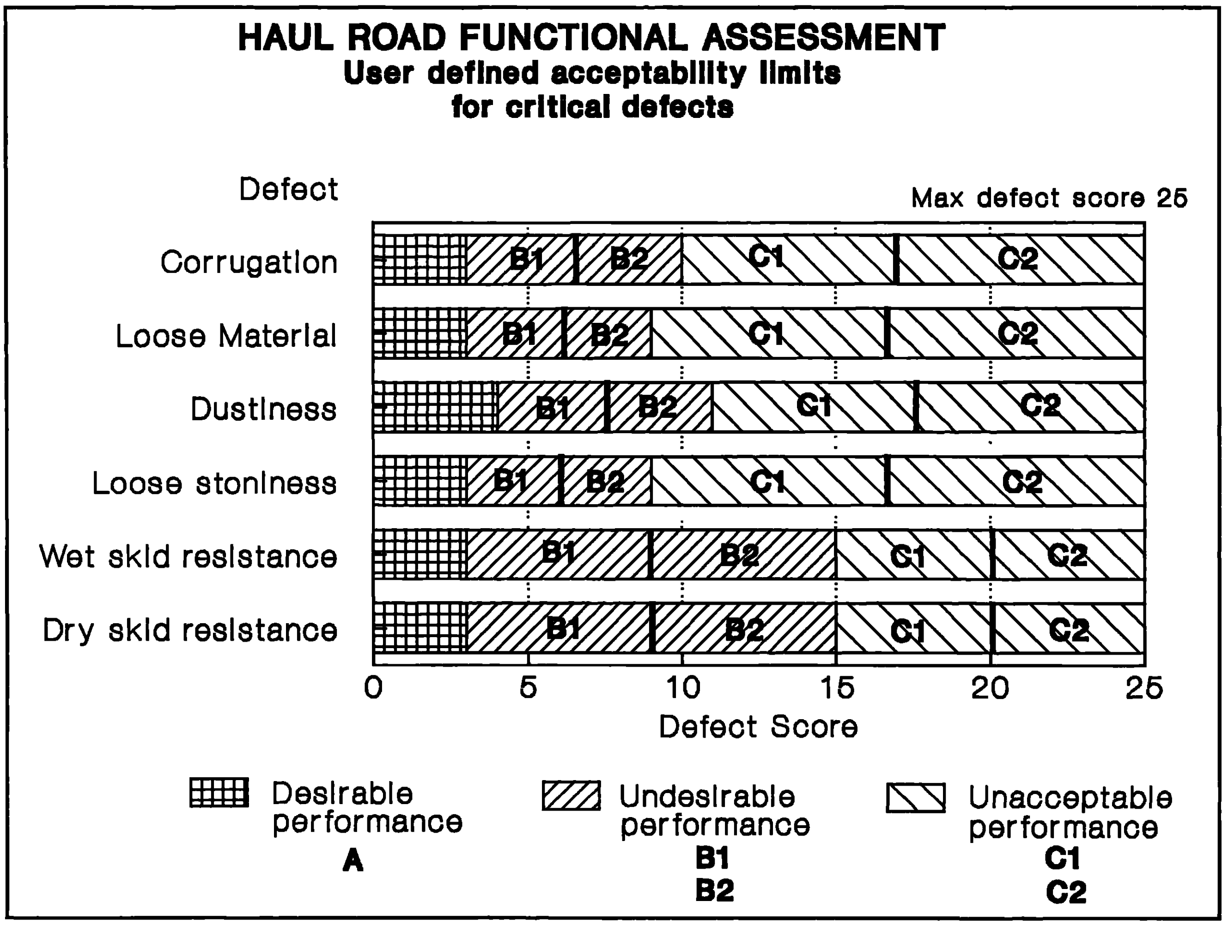


Figure 12.1 Graphical Representation of Defect and Overall Road Functional Performance Classification.

From Figure 12.1 two defect groups are apparent in terms of acceptability limits; wet and dry skid resistance exhibiting higher undesirable and unacceptable limits than the other defects. The sub-divided performance classification limits for both critical defect groups are given in Table 12.3 based on the modal classification limits for each group. The concept of "operability" has been used in developing the classification, where operable roads are considered to exist up to and including the upper limit of unacceptable performance (C1). The specific operability limit would normally be associated with traffic volumes etc. (lower limits being applied to less frequently trafficked roads) but for the purposes of comparison and specification development, the single operability limit is adopted.

Table 12.3 Acceptability Limits for Critical Functional Defects.

ACCEPTABILITY LIMITS FOR CRITICAL FUNCTIONAL DEFECTS.				
	Acceptability limits of defect score			
Acceptability level	▪Corrugation ▪Loose material ▪Dustiness ▪Loose stoniness	▪Wet skid resistance ▪Dry skid resistance	**Description of acceptability limits**	**Operability limits**
A	<5	<5	Desirable	Operable
B1	5 - 7	5 - 10	Undesirable (upper)	
B2	8 - 10	11 - 15	Undesirable (lower)	
C1	11 - 17	16 - 20	Unacceptable (upper)	
C2	>17	>20	Unacceptable (lower)	Inoperable

The acceptability levels defined in Table 12.3 may also be used to classify overall functional performance of a road, in this case using a maximum (total) defect score of 150 (representing 6 critical defects each with a maximum defect score of 25) as given in Table 12.4. This approach assumes each defect carries equal significance in terms of its impact on safety, production, truck and tyre. It was shown in Chapter 11 that each critical defect could be weighted according to its impact on functionality. These weighting factors were applied to each critical defect score to derive an overall weighted functional classification of the road as given in Table 12.4. In this manner, those critical defects which significantly affect road functionality are emphasised in the overall classification (ie. a road exhibiting a high wet skid resistance defect score would be accorded a lower classification than would be the case if the same high defect score were associated with the corrugation defect, all other defect scores being similar).

Table 12.4 Acceptability Limits for Overall Functional Performance.

<table>
<tr><th colspan="5">ACCEPTABILITY LIMITS FOR OVERALL HAUL ROAD FUNCTIONAL PERFORMANCE.</th></tr>
<tr><th></th><th colspan="2">Acceptability limits of overall defect score[1]</th><th colspan="2"></th></tr>
<tr><th>Acceptability level</th><th>Unweighted (max score 150)</th><th>Weighted (max score 350)</th><th>Description of acceptability limits</th><th>Operability limits</th></tr>
<tr><td>A</td><td><30</td><td><70</td><td>Desirable</td><td rowspan="4">Operable</td></tr>
<tr><td>B1</td><td>31 - 48</td><td>71 - 112</td><td>Undesirable (upper)</td></tr>
<tr><td>B2</td><td>49 - 66</td><td>113 - 154</td><td>Undesirable (lower)</td></tr>
<tr><td>C1</td><td>67 - 108</td><td>155 - 252</td><td>Unacceptable (upper)</td></tr>
<tr><td>C2</td><td>>108</td><td>>252</td><td>Unacceptable (lower)</td><td>Inoperable</td></tr>
<tr><td colspan="5">NOTES
1. Limits of acceptability for weighted and unweighted overall classification derived from individual defect acceptability limits (Table 12.3).</td></tr>
</table>

12.3 Specification Development

Using the acceptability levels (A-C2) determined in Tables 12.3 and 12.4 it is possible to investigate material property and performance relationships both in terms of overall test site performance and the individual defect contribution to overall performance. In addition, the utility of existing guidelines can be assessed in terms of the extent to which such guidelines accommodate and reflect the various overall and individual defect rankings.

12.3.1 Assessment of Material Property and Performance Relationships

From the statistical analysis and modelling of overall road and individual defect functional performance presented in Chapter 10, the material parameters of plasticity and grading were identified as primarily controlling the functional performance of a haul road. Specifically the grading coefficient (GC), dust ratio (DR), shrinkage product (SP), plasticity index (PI) and liquid (LL) and plastic (PL) limits were found to contribute to the rate of defect score increase or decrease. Accordingly, the specific material property values derived from Tables 3.8-3.11 were classified according to the overall road or individual defect acceptability levels (between A-C2 as presented in Tables 12.3 and 12.4) in an attempt to determine wearing course material property limits.

The relative significance of each critical defect analysed is important when an overall classification of performance and associated material properties is attempted. More importance should be attached to those material properties associated with the more critical functional defects. This was achieved by incorporating the defect weighting factors derived from Table 11.7 in the classification, as described earlier. In this manner, overall performance is related to the criticality of a defect, those with high ranking scores contribute proportionally more to the overall ranking. Using the mine test site monthly defect scores an average defect score was calculated for the 12 month monitoring period, representing conditions that should not be exceeded 50% of the time. Spurious high or low defect scores (associated with conditions immediately after maintenance or rainfall, etc.) were ignored. Table 12.5 presents the results of the overall functional performance classification for each of the 11 mine sites analysed using weighted and unweighted overall scores. Table 12.6 presents the corresponding material property values for the unweighted overall performance whilst Table 12.7 the property values for the weighted overall performance.

The range of material properties encountered was found to be limited as discussed in Chapter 10 and thus no statistically significant material property relationships with performance ranking are observed in Table 12.6 or 12.7 but some general trends can be hypothesised. It is seen that the effect of including weights in the analysis downgrades the performance of two test sites (Kriel site 1 and Kromdraai site 2) due to a relatively large dustiness defect score at these sites. The classification of the other sites however remained similar. Grading of the material, as represented by the grading coefficient appears to increase with decreasing levels of functional performance. This may be related to the propensity of the wearing course to generate loose material, however, the bounds cannot

Table 12.5 Overall Mine Site Functional Performance Classification

OVERALL FUNCTIONAL PERFORMANCE CLASSIFICATION										
	Corrected average defect scores for critical defects						Weights applied (according to defect ranking, Table 5.7)		No weights applied	
Mine Site	Corrugations	Loose material	Dustiness	Loose stoniness	Wet skid resistance	Dry skid resistance	Overall functional performance score	Performance classification	Overall functional performance score	Performance classification
Kriel 1	4,1	10,0	11,4	6,7	17,5	15,6	163,2	C1	65,3	B2
Kriel 2	4,7	9,8	14,3	8,4	23,8	17,0	196,8	C1	77,9	C1
Kriel 3	4,5	10,3	9,4	5,3	15,0	15,0	147,9	B2	59,5	B2
Kromdraai 1	3,6	11,9	12,6	6,3	15,4	17,0	167,5	C1	67,2	C1
Kromdraai 2	3,6	8,3	16,3	8,4	15,5	12,5	161,0	C1	64,5	B2
Kromdraai 3	3,1	12,4	8,1	1,2	15,0	15,0	138,7	B2	54,9	B2
New Vaal 1	5,2	10,2	11,0	4,8	15,0	17,3	142,4	B2	57,5	B2
New Vaal 2	3,7	7,9	8,1	5,8	16,1	14,1	139,8	B2	55,7	B2
New Vaal 3	8,3	16,0	18,7	8,3	15,8	18,1	208,0	C1	85,3	C1
Kleinkopje 1	4,0	9,3	18,1	7,6	15,0	15,0	172,5	C1	69,0	C1
Kleinkopje 2	4,3	11,4	19,3	11,8	16,0	15,7	193,3	C1	78,0	C1

Table 12.6 Material Parameter Relationship to Overall Unweighted Functional Performance Classification

MATERIAL PARAMETER VARIATION WITH FUNCTIONAL PERFORMANCE RANKING OVERALL UNWEIGHTED FUNCTIONAL PERFORMANCE						
PERFORMANCE RANKING	**DR**	**LL**	**PI**	**PL**	**GC**	**SP**
B2	0.4	21.0	4.0	17.0	30.1	82.0
	0.4	17.0	5.0	12.0	31.1	90.0
	0.6	23.0	8.0	15.0	21.3	196.0
	0.5	24.0	8.0	16.0	28.7	128.0
	0.4	18.0	4.0	14.0	24.8	102.0
	0.5	21.0	6.0	15.0	30.7	111.0
Average	***(0.5)***	***(20.7)***	***(5.8)***	***(14.8)***	***(27.8)***	***(118.2)***
C1	0.6	24.0	8.0	16.0	30.9	160.0
	0.6	24.0	10.0	14.0	36.3	198.0
	0.4	22.0	5.0	17.0	26.2	72.0
	0.6	23.0	7.0	16.0	28.8	164.5
	0.5	22.0	7.0	15.0	27.7	178.5
Average	***(0.5)***	***(23.0)***	***(7.4)***	***(15.6)***	***(30.0)***	***(154.6)***

easily be established from the available data. It may be anticipated that as the grading coefficient decreases a lower limit will be seen beyond which the erosion of fine binding material becomes problematic. No trend was evident in the dust ratio but the shrinkage product appears to increase with decreasing levels of functional performance indicating that both fine material (dust) and wet slipperiness are problematic as this property parameter increases. For the material parameters associated with plasticity, in general terms increasing parameter values appear to be associated with a lower classification, however, no lower bounds are apparent. Some degree of material plasticity is required to reduce the propensity of the wearing course to form loose material. However, excessive plasticity will result in both increased dust and wet slipperiness defects.

Table 12.8 presents the individual defect functional performance classification whilst Appendix I contains the associated tabulations of material property value variation with

Table 12.7 Material Parameter Relationship to Overall Weighted Functional Performance Classification

MATERIAL PARAMETER VARIATION WITH FUNCTIONAL PERFORMANCE RANKING OVERALL WEIGHTED FUNCTIONAL PERFORMANCE						
PERFORMANCE RANKING	**DR**	**LL**	**PI**	**PL**	**GC**	**SP**
B2	0.4	21.0	4.0	17.0	30.1	82.0
	0.4	17.0	5.0	12.0	31.1	90.0
	0.4	18.0	4.0	14.0	24.8	102.0
	0.5	24.0	8.0	16.0	28.7	128.0
Average	***(0.4)***	***(20.0)***	***(5.3)***	***(14.8)***	***(28.7)***	***(100.5)***
C1	0.6	24.0	8.0	16.0	30.9	160.0
	0.4	22.0	5.0	17.0	26.2	72.0
	0.5	21.0	6.0	15.0	30.7	111.0
	0.6	24.0	10.0	14.0	36.3	198.0
	0.6	23.0	8.0	15.0	21.3	196.0
	0.6	23.0	7.0	16.0	28.8	164.5
	0.5	22.0	7.0	15.0	27.7	178.5
Average	***(0.5)***	***(22.7)***	***(7.3)***	***(15.4)***	***(28.8)***	***(154.3)***

individual defect classification. Again no statistically significant relationships may be deduced and there is considerable variation in parameter values within each classification group, nevertheless, some general observations may be made. The loose material defect is associated with the shrinkage product parameter, such that reducing values cause a deterioration in the loose material defect. Dustiness may be associated with both shrinkage product and grading coefficient such that intermediate values of both give the best result; extremely high or low values being problematic in terms of dust or erosion and ravelling. No trends were discerned for loose stoniness although the liquid limit of the material may be implicated in releasing loose stones as a result of shrinkage. The amount of large stones in the wearing course material is also important in this respect but was not analysed as a material property variable. The remaining defects did not reveal any significant trends in parameter value variation with defect classification primarily due to the limited range of

Table 12.8 Individual Defect Functional Performance Classification

INDIVIDUAL DEFECT FUNCTIONAL PERFORMANCE CLASSIFICATION Corrected defect score (degree x extent) for critical defects												
Mine Site	**Corrugations**	**Functional classification**	**Loose material**	**Functional classification**	**Dustiness**	**Functional classification**	**Loose stoniness**	**Functional classification**	**Wet skid resistance**	**Functional classification**	**Dry skid resistance**	**Functional classification**
Kriel 1	4,1	*A*	10,0	*B2*	11,4	*C1*	6,7	*B1*	17,5	*C1*	15,6	*B2*
Kriel 2	4,7	*A*	9,8	*B2*	14,3	*C1*	8,4	*B2*	23,5	*C2*	17,0	*C1*
Kriel 3	4,5	*A*	10,3	*B2*	9,4	*B2*	5,3	*B1*	15,0	*B2*	15,0	*B2*
Kromdraai 1	3,6	*A*	11,9	*C1*	12,6	*C1*	6,3	*B1*	15,9	*B2*	17,0	*C1*
Kromdraai 2	3,6	*A*	8,3	*B2*	16,3	*C1*	8,4	*B2*	15,5	*B2*	12,5	*B2*
Kromdraai 3	3,1	*A*	12,4	*C1*	8,1	*B2*	1,2	*A*	15,0	*B2*	15,0	*B2*
New Vaal 1	5,2	*B1*	10,2	*B2*	11,0	*B2*	4,8	*A*	14,0	*B2*	17,3	*B2*
New Vaal 2	3,7	*A*	7,9	*B1*	8,1	*B2*	5,8	*B1*	16,1	*C1*	14,1	*B2*
New Vaal 3	8,3	*B2*	16,0	*C1*	18,7	*C2*	8,3	*B2*	15,8	*B2*	18,1	*C1*
Kleinkopje 1	4,0	*A*	9,3	*B2*	18,1	*C2*	7,6	*C1*	15,0	*B2*	15,0	*B2*
Kleinkopje 2	4,3	*A*	11,4	*C1*	19,3	*C2*	11,8	*C1*	16,0	*B1*	15,7	*B2*

values encountered. This may be indicative of preselection of wearing course materials encountered on the mines such that functional performance approaches optimal.

12.3.2 Assessment of TRH20 Specifications in Relation to Performance Ranking

The TRH20 (CSRA, 1990) wearing course material selection guidelines were developed from functional performance considerations of unpaved public roads as described in Chapter 2.3. The selection criteria for mine haul roads were discussed by Paige-Green (1989) in his development of the guidelines. A shrinkage product of 100-365 (preferably less than 240) together with a grading coefficient of 16-34 are recommended in the light of slipperiness and traction considerations. Figure 12.2 illustrates the location of each mine test site in terms of shrinkage product and grading coefficient values whilst the overall site classification is presented in Figure 12.3, the latter illustrating only a small portion of the graph. From these figures it is clear that the majority of the mine sites lie within the recommended (Paige-Green, 1989) material selection limits (a'b'c'd'). Of those sites lying outside the recommended limits (R1, R3, N1 and N3), only sites R1 and N3 exhibited excessive ravelling and corrugation defects.

The overall functional classification shown in Figure 12.3 reveals that most of the test sites exhibited undesirable (lower B2) to unacceptable (upper C1) performance, albeit operable. Of those sites lying outside the recommended limits (R1, R3, N1 and N3), only sites R1 and N3 exhibited unacceptable performance (upper C1) and thus should be excluded from the recommended selection range for mine haul road wearing course materials. The individual defect classifications are given in full in Appendix I and are summarised in Figure 12.4 in which approximate trends in defect increase are shown. The corrugation defect appears to increase with reducing grading coefficient and shrinkage product, confirming that low plasticity materials are more prone to corrugation. The loose material and dry skid resistance defects increase with increasing grading coefficient and decreasing shrinkage product, the lack of binder in gap graded sandy gravels resulting in loose material and adverse dry skid resistance. The dustiness defect increases as grading coefficient decreases and shrinkage product increases, reflecting an increase in the amount of fine material present in the wearing

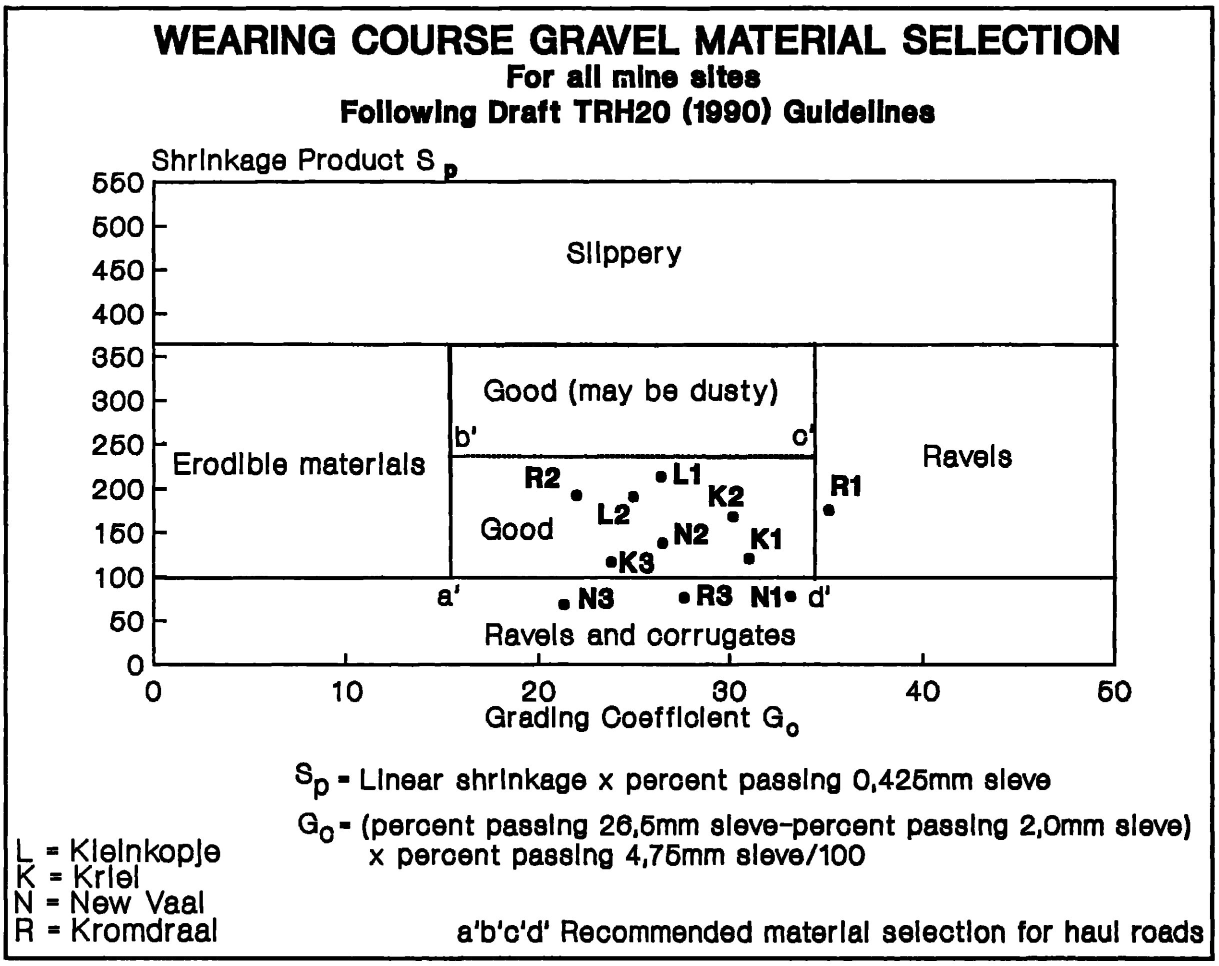


Figure 12.2 Location of mines sites in terms of TRH20 selection guidelines.

course. Although dust palliatives are used on mine haul roads, a dust defect exists above acceptable levels (as defined by the road-user) for even the most suitable material types analysed. The application of palliatives is currently performed on an ad-hoc basis. It would thus appear necessary to further investigate the use of surface treatments which, in addition to reducing haul road dust defect scores to acceptable levels, would also simultaneously improve the other critical defects. The wet skid resistance defect classification did not reveal any significant trend but it may be hypothesised that an increase in fine clay fraction material may result in adverse wet skid resistance. The ambiguity associated with these trends arises as a result of the mutual interference or reinforcement of defects due to the various material parameter combinations encountered. This is evidenced in the classification tables presented in Appendix I.

All of the above trends are recognised within or close to the recommended material selection

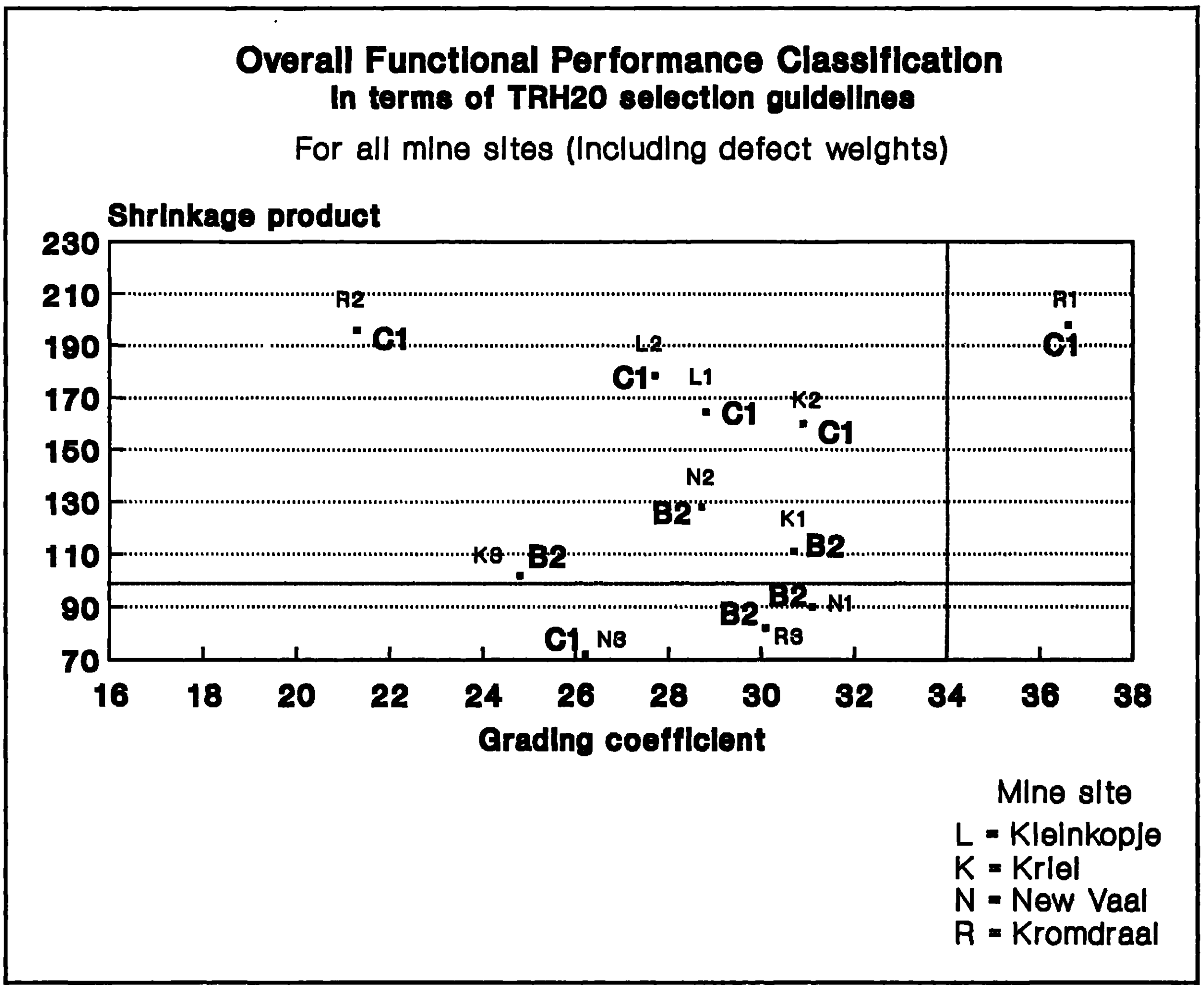


Figure 12.3 Overall mine site functional performance classification in relation to TRH20 specifications.

limits proposed by Paige-Green (1989) and ideally points outside this area are required to confirm these trends. It is apparent that the TRH20 specifications provide a suitable base for material specification and in addition, reflect the typical defect associated with departure from the specifications. If the three most critical defects are considered in the light of the TRH20 specifications it appears that road-use preference is for much reduced wet skid resistance, dust and dry skid resistance defects at the expense of an increase in the other defect scores. This alters the focus point of the specifications to an area bounded by a grading coefficient of 25-32 and a shrinkage product of 95-130 in which the overall and individual defect performance is optimised. Extending this region to encompass poorer overall performance enables an additional area to be defined as given in Table 12.9 and Figure 12.4.

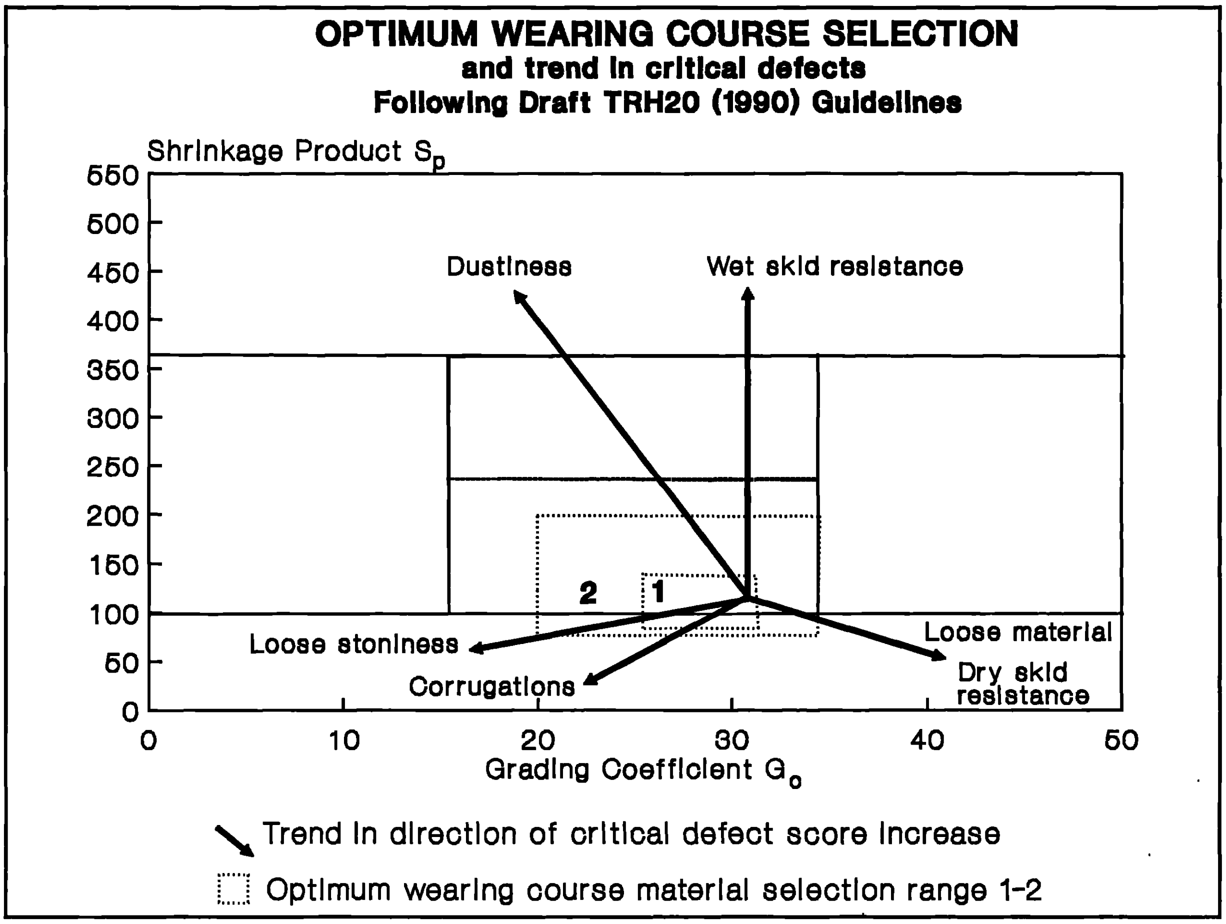


Figure 12.4 Optimum Material Selection Ranges and General Trends of Increasing Defect Scores.

Table 12.9 Grading Coefficient and Shrinkage Product Limits for Areas of Optimal Functional Performance (given in Figure 12.4)

OPTIMUM MATERIAL RANGES BASED ON TRH20 SPECIFICATIONS					
AREA	**Shrinkage Product Min**	**Shrinkage Product Max**	**Grading Coefficient Min**	**Grading Coefficient Max**	**Average Performance Classification**
1	95	130	25	32	B2
2	85	200	20	35	B2/C1

12.4 Wearing Course Material Selection Guidelines

The suitability of the TRH20 technique of wearing course material selection based on grading coefficient and shrinkage product parameters has been established together with a range over which optimal performance is assured. This approach should be tempered through the consideration of the other material properties identified as important in functional performance but not directly assessed in the TRH20 technique. Table 12.10 presents a summary of these property limits, derived from the data analysed in Chapters 9 and 10 and Appendix I.

Table 12.10 Recommended Parameter Ranges for Wearing Course Material Selection

WEARING COURSE MATERIAL SELECTION PARAMETERS			
Material Parameter	**Range** **Min**	 **Max**	**Impact on Functionality**
Shrinkage Product	85	200	Reduce slipperiness but prone to ravelling and corrugation
Grading Coefficient	20	35	Reduce erodibility of fine materials, but induces tendency to ravel
Dust Ratio	0,4	0,6	Reduce dust generation but induces ravelling
Liquid Limit (%)	17	24	Reduce slipperiness but prone to dustiness
Plastic Limit (%)	12	17	Reduce slipperiness but prone to dustiness
Plasticity Index	4	8	Reduce slipperiness but prone to dustiness and ravelling
CBR at 98% Mod AASHTO	80		Resistance to erosion, rutting and improved trafficability
Maximum Particle Size (mm)		20	Ease of maintenance and vehicle friendly ride

Wearing course material specifications associated with the structural design of mine haul roads have been proposed (Thompson and Visser, 1994) in terms of TRH14 (NITRR, 1985). In addition, haul road design work (Anglo American Corporation (AAC), 1994) also currently specifies material requirements in terms of TRH14 and it is thus useful to consider the equivalence of the latter to the modified specifications established in Table 12.9. Material available on site for the construction of the wearing course is derived from borrow pits comprising generally ferricrete and is classified (following TRH14) as G4-G7. Using G4 material specifications a location range can be determined for the equivalent TRH20 specification. The range of grading coefficient lies between 12 and 52 and that of shrinkage product between 30 and 90 (for the full allowable grading variability specified in TRH14). Whilst the grading coefficient parameter encompasses materials liable to erode and to ravel, the shrinkage product lies in the range of material types associated with ravelling and corrugation only. If poorer quality materials are considered (G5-G7), although no specific grading requirements are given in TRH14, the increase in allowable linear shrinkage should improve the location range of these materials in terms of the optimum haul road material selection parameter ranges given in Table 12.9. It is clear that TRH14 alone does not provide sufficient differentiation between material parameters and haul road defects to enable it to be used as a specification for mine haul road wearing course material selection.

12.5 Summary and Conclusions

The derivation of wearing course material selection guidelines was based on the identification, characterisation and ranking of haul road functional defects. A reference framework was developed within which suitable specifications should fall, based on an assessment of the requirements of good specifications in the light of functional defect ranking and acceptability limits. Two approaches were adopted in deriving suitable specifications. Initially, the important material property parameters controlling both functional performance and individual defect score progression rates were assessed in relation to an overall haul road functional performance classification to identify likely trends and limits for individual parameter values. The classification system adopted included five categories of performance, from desirable to unacceptable and included an estimation of limits on operability of the road. When individual defects were considered in terms of this ranking it was found that only general trends could be deduced from the data since only a limited range of parameter variation was evident. In addition, the defect limiting acceptability criteria established in

Chapter 11 appear unrealistic in terms of the higher operable limits derived from this analysis. A similar effect was seen when overall road operable functionality was compared to the limits derived from acceptability testing. It is apparent that desirable functional performance (as defined by road-user assessment of functionality) can only be achieved with currently available wearing course materials if some additional material treatment is applied. The use of suitable surface treatments should be investigated from the point of view of a simultaneous reduction in the wet skid resistance, dry skid resistance, loose material and dust critical defects. In this respect, the use of bituminous additives may afford the most tractable approach to defect ameliorisation.

The suitability of existing wearing course material selection guidelines proposed in TRH20 for mine haul road material specification were also analysed. A revised range of parameters was derived based on the road-user preference for much reduced wet slipperiness, dustiness and dry skid resistance defects. A summary of the proposed haul road wearing course material specifications and those of TRH20 are given in Table 12.11.

Table 12.11 Recommended Parameter Ranges for Wearing Course Material Selection in Comparison to TRH20 Specifications.

MATERIAL PARAMETER	HAUL ROAD WEARING COURSE MATERIAL SELECTION GUIDELINES		TRH20 SPECIFICATIONS	
	Range		Range	
	Min	Max	Min	Max
Shrinkage Product	85	200	100	365 (preferably <240)
Grading Coefficient	20	35	16	34
CBR at 98% Mod AASHTO	80		15[1]	
Maximum Particle Size (mm)		20		75-100[2]

Notes
1. CBR specified at 95% Mod AASHO compaction and 4-days soaking, to account for greater traction forces exerted by vehicles.
2. Specifications include an oversize index I_o defined as the percent of material retained on the 37,5mm sieve.

By analysing the trends evident in the individual defects rankings, the predictive capability of the specification was enhanced in terms of likely functionality problems when departures are made from recommended parameter limits. The TRH14 material classification system was found to be inadequate as a base for haul road wearing course material selection due to its inability to adequately differentiate between critical defects over the range represented by typical haul road construction materials.

The data used in the analysis and derivation of the selection parameters was based on material samples gathered after compaction and the specification should ideally be applied to compacted materials as opposed to borrow-pit samples. With the shrinkage product specification an increase may be expected during compaction due to degradation of the (particularly poorer quality) materials. In addition, good construction and drainage is implicit in the specifications; where poor drainage, construction or compaction is evident the functional performance of the road will be inadequate despite optimal material selection.

CHAPTER 13
ROAD ROUGHNESS PROGRESSION MODEL

13.1 Introduction

The proposed mine haul road maintenance management system (MMS) is illustrated in Figure 2.5 from which it is seen that the road roughness progression model forms the basis of the MMS. Roughness is the principal measure of pavement condition that can be directly related to both vehicle operating costs and the frequency of maintenance activities as shown in Figure 3.12. A realistic mine haul road roughness progression model is therefore required to enable road roughness and maintenance frequency effects to be investigated. Table 3.14 presents a summary of the road roughness progression model data requirements. This chapter addresses those requirements in terms of the development of a roughness progression model based on the increase in roughness (measured as rolling resistance), together with the correlation of rolling resistance to both a subjectively derived roughness defect score and the equivalent quantitative International Roughness Index (m/km IRI) to enable meaningful comparison and ensure portability of the technique.

13.2 Subjective Evaluation of Road Roughness

In the analysis of the current state of mine haul road management presented in Chapter 2.4 it was found that existing road roughness assessments were generally highly subjective and localised in nature and did not rigorously assess the contributory components of road roughness. In a first step to providing a rigorous and portable approach to road roughness evaluation which would permit the development of a progression model, a qualitative roughness assessment technique was developed based on the contributory roughness defects of potholes, corrugations, rutting, loose material and fixed stoniness.

The condition of the pavement is considered from the point of view of the road-user and incorporates appraisal in terms of the contributory factors to road roughness. The approach and evaluation criteria for the particular defects associated with road roughness is similar to that described in Chapter 9. This provides for both reduced subjectivity in the analysis of each contributory defect and for the use of selected defect data generated from the functionality assessment in developing a roughness defect progression model. The recording form is shown in Figure 13.1 whilst the associated defect degree and extent classifications are given in Tables 13.1 and 13.2.

UNIVERSITY OF PRETORIA
DEPARTMENTS MINING AND CIVIL ENGINEERING
HAUL ROADS RESEARCH PROJECT

SUBJECTIVE EVALUATION OF ROAD ROUGHNESS

MINE: ....
DATE: ....
HAUL ROAD: ....
SEGMENT: ....

DEFECT	DEGREE 1	DEGREE 2	DEGREE 3	DEGREE 4	DEGREE 5	EXTENT 1	EXTENT 2	EXTENT 3	EXTENT 4	EXTENT 5
POTHOLES										
CORRUGATIONS										
RUTTING										
LOOSE MATERIAL										
STONINESS - FIXED										

COMMENTS AND OBSERVATIONS

Figure 13.1 Recording form for subjective haul road roughness evaluation.

Table 13.1 Classification of the Extent of Haul Road Roughness Defect Aspects to be Evaluated.

EXTENT	DESCRIPTION
1	Isolated occurrence, less than 5% of road affected.
2	Intermittent occurrence, between 5-15% of road affected.
3	Regular occurrence, between 16-30% of road affected.
4	Frequent occurrence, between 31-60% of road affected.
5	Extensive occurrence, more than 60% of the road affected.

Table 13.2 Classification of the Degree of Haul Road Roughness Defect to be Evaluated.

CHARACTERISTIC DEFECT	DESCRIPTION				
	Degree 1	Degree 2	Degree 3	Degree 4	Degree 5
Potholes	Surface is pock marked, holes < 50mm diameter.	Potholes 50-100mm diameter.	Potholes 100-400mm diameter and influence riding quality.	Potholes 400-800mm diameter, influence riding quality and obviously avoided by most vehicles.	Potholes >800mm diameter, influence riding quality and require speed reduction or total avoidance.
Corrugations	Slight corrugations, difficult to feel in light vehicle.	Corrugations present and noticeable in light vehicle.	Corrugations very visible and reduce riding quality noticeably.	Corrugations noticeable in haul truck and causing driver to reduce speed.	Corrugations noticeable in haul truck and causing driver to reduce speed significantly.
Rutting	Difficult to discern unaided, <20mm.	Just discernable with eye, 20-50mm.	Discernable, 50-80mm.	Obvious from moving vehicle, >80mm.	Severe, affects direction stability of vehicle.
Loose material	Very little loose material on road, <5mm depth.	Small amount of loose material on road to a depth of 5-10mm.	Loose material present on road to a depth of 10-20mm.	Significant loose material on road to a depth of 20-40mm.	Considerable loose material, depth >40mm.
Stoniness - fixed in wearing course	Some protruding stones, but barely felt or heard when travelling in light vehicle.	Protruding stones felt and heard in light vehicle.	Protruding stones influence riding quality in light vehicle but still acceptable.	Protruding stones require evasive action of light vehicle.	Protruding stones require evasive action of haul truck.

NOTE. 1. Description of degrees refers to haul truck unless otherwise stated.
2. Rutting - depressions extended in length and limited in width, usually occurring in a longitudinal direction and in the wheel path.
3. Corrugations - regularly spaced transverse undulations of the pavement at regular intervals less than 1m apart or erosion gulleys in the road perpendicular to the direction of travel.

13.3 Correlation of Subjective Evaluation of Roughness with IRI

To ensure portability of the road roughness evaluation technique, each mine haul road was evaluated simultaneously both in terms of the sum of component defect degree and extent scores for each 100m section of road and the equivalent quantitative IRI roughness over the same section. The IRI is a summary index of the irregularity of the road profile in the wheelpath and quantifies the impact of roughness on a moving vehicle in much the same way as vibrations induced by roughness influence vehicle operating costs and hence is considered to be the most applicable measure of roughness for use in economic evaluation purposes (Paterson, 1987).

The IRI was generated by means of a high speed profilometer (HSP) vehicle as described in Chapter 3. Longitudinal profiles were generated for each wheel track (inner and outer laden and unladen carriageways) based on displacement readings taken every 246.55mm and averaged over 100m sections to give IRI (m/km) values for each wheel track every 100m using the PROROUGH program (PROROUGH, 1995). Figure 13.2 shows a typical IRI roughness profile generated for each wheel track. Full results are presented in Appendix J from which it is seen that roughness is similar in each wheel track with slightly more damage being evident on the laden side of the road.

Figure 13.3 presents a comparison between the subjective defect scores for each 100m section and the IRI values for each section calculated on the basis of the section maximum, average or minimum IRI. The best match between subjective defect scores and IRI is seen when the maximum IRI score is used since the subjective evaluation technique is predisposed to identifying the worst conditions over the section of road. No improvement in correlation was seen when further analyses were conducted to determine if weighting particular defect degree or extent scores improved the correlation, based on the hypothesis that certain defects may contribute more to measured displacement (and hence IRI) than others. Full results of the associated sectional defect scores are presented in Appendix K.

The correlation between IRI_{max} (m/km) and roughness defect score (RDS) is given in Equation [13.1a] whilst Equation [13.1b) gives the correlation between IRImax and IRI.

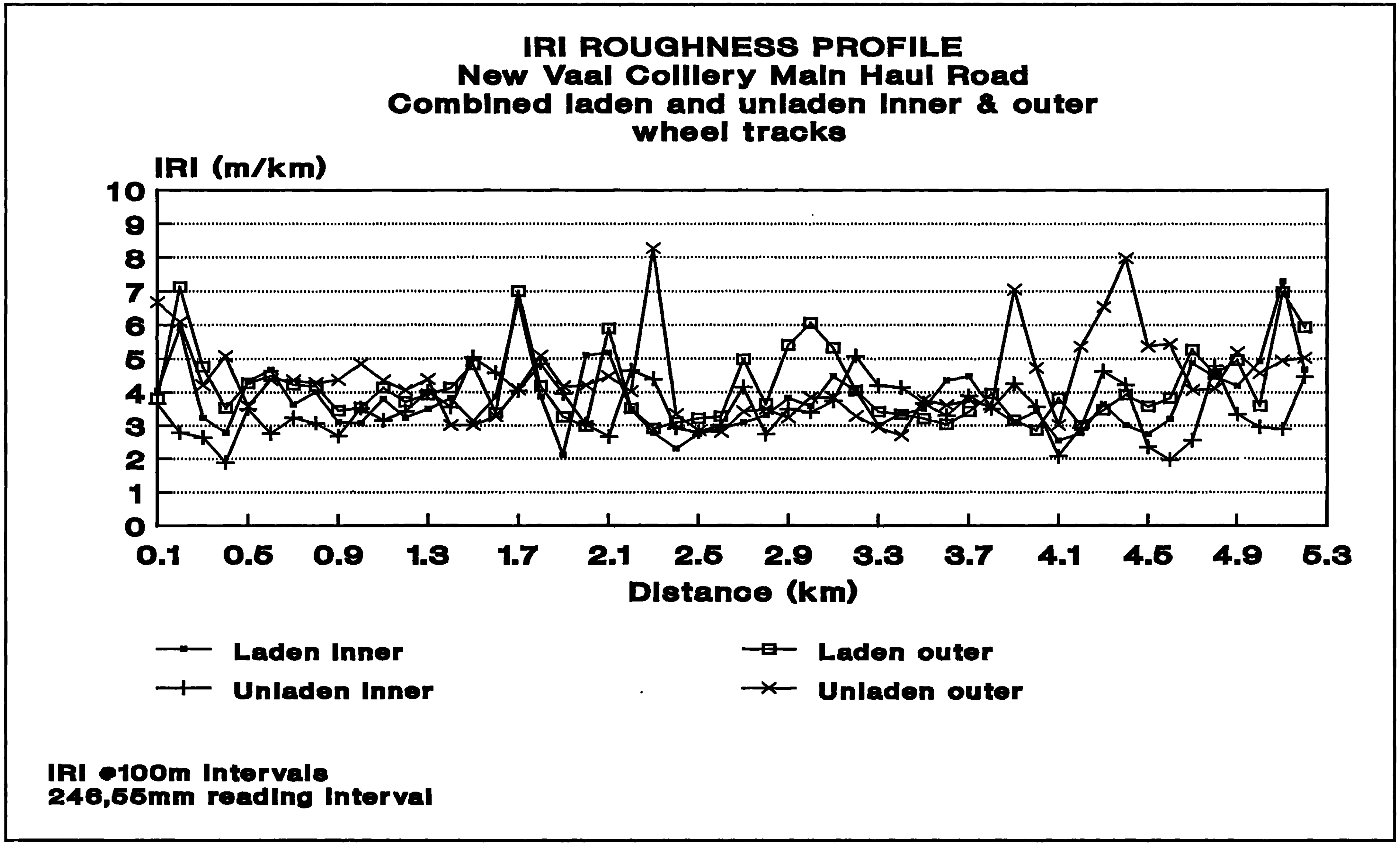


Figure 13.2 Typical IRI roughness profiles for laden and unladen carriageways, inner and outer wheel paths.

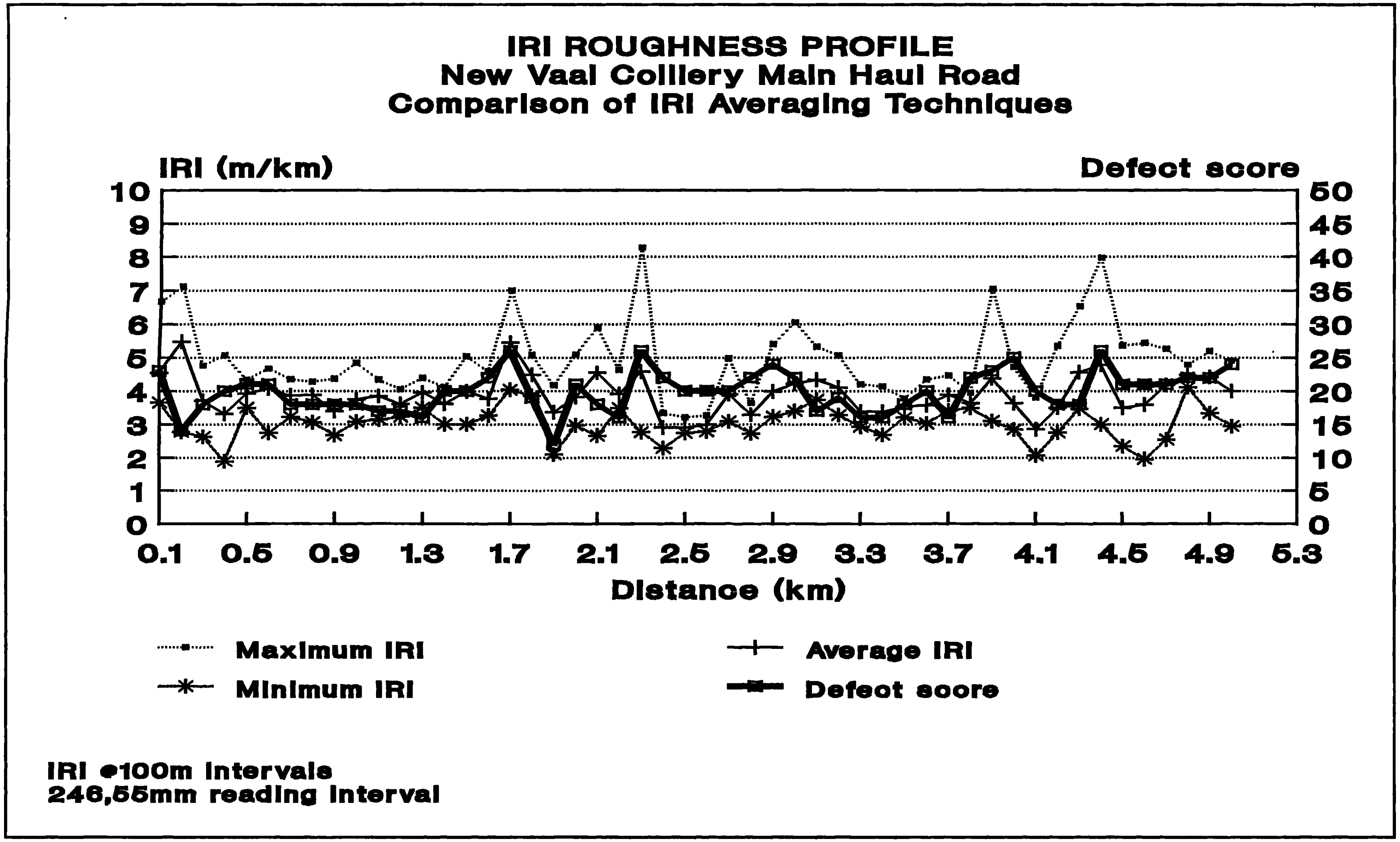


Figure 13.3 Comparison of maximum, average and minimum IRI roughness with roughness defect score

Both are illustrated in Figure 13.4.

$$\begin{aligned} IRI_{max} &= 3{,}1641 + 0{,}1155.RDS && (a) \\ IRI_{avg} &= 3{,}0556 + 0{,}0641.RDS && (b) \end{aligned} \qquad (13.1)$$

The model for IRI_{max} has an R-squared value of 34%, F value of 159,3 which is highly significant for a sample size of 304. For the standard error of the model of 1,037, the approximate 95% confidence intervals for an IRI_{max} roughness score of 10 lie between 7,92 and 12,07. Equation [13.1b] is also given as a means by which results may be converted to the standard (average) IRI scores. This model has an R-squared value of 24%, F value of 114,0 and a standard error of 1,677. Full statistics for the models are given in Table 13.3. Although the R-squared values are relatively low, the large number of observations result in a significant correlation. A contributory factor to the low R-squared values may be ascribed to the limited aerial extent of the HSP evaluation in which wheel tracks only were followed in comparison to the subjective evaluation which was carried out over the full width of the road. Another contributory factor was the change in roughness induced by the combination of rain and traffic on the Kriel Colliery road. During HSP profiling it was observed that divots of mud ejected from haul truck tyres contributed to larger IRI roughness values. The subjective assessment was conducted whilst the road was dry and as such did not assess this aspect of roughness directly, rather indirectly in terms of loose material which, when wet, forms the source of these divots. Although not contributing to roughness in the same sense as potholes or corrugations, etc. they nevertheless contribute to rolling resistance. The aspect of road roughness defects and the associated rolling resistance is more fully discussed in the following section.

13.4 Analysis of Rolling Resistance and Roughness Defect Score Relationship

For the propulsion of a vehicle, power is necessary to overcome mechanical losses in the power transmission itself prior to a number of motion-related resistances;

- surface rolling resistance
- air resistance

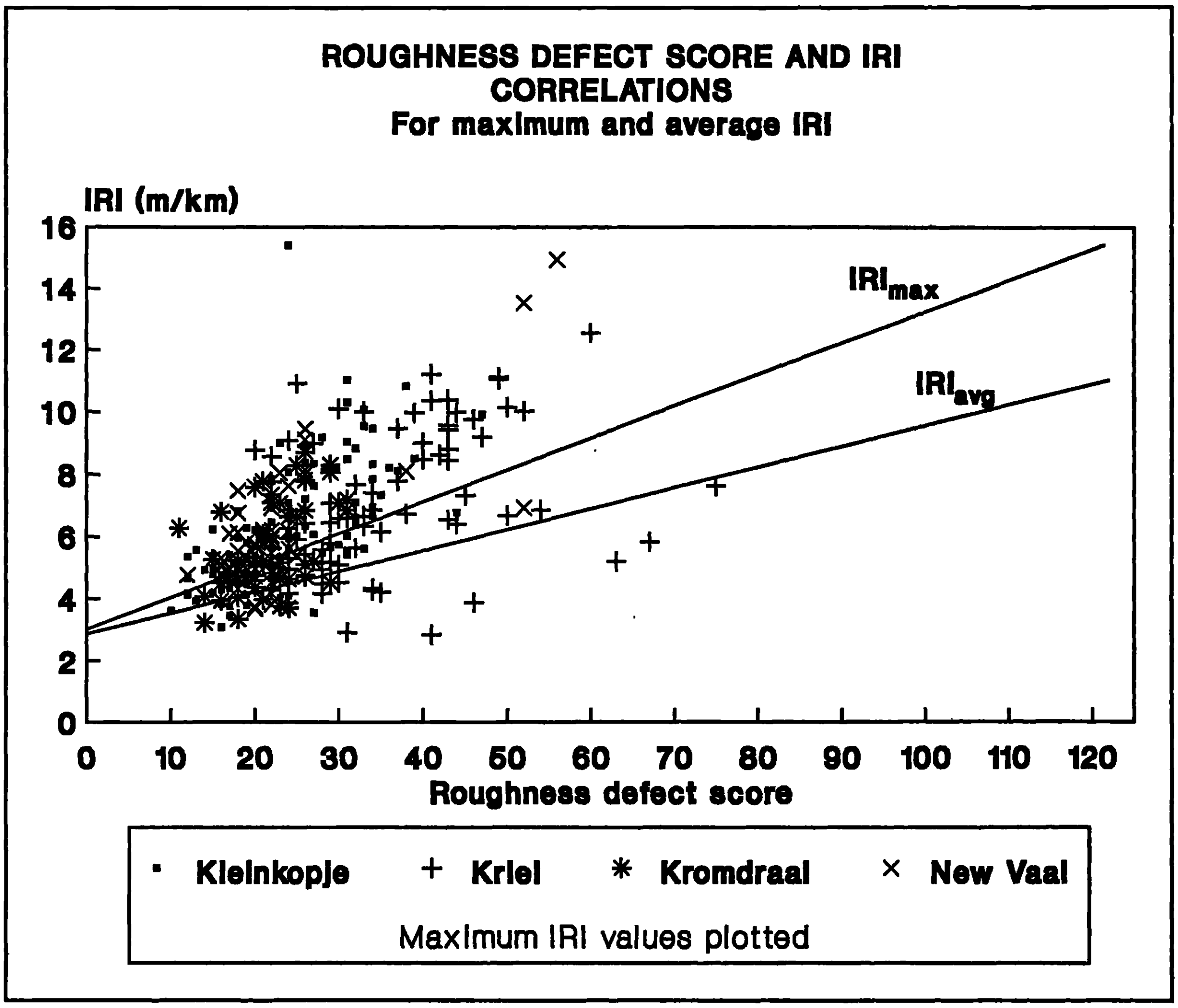


Figure 13.4 Correlation between IRI and RDS data and model.

Table 13.3 IRI and Roughness Defect Score Correlation Statistics

STATISTICS OF CORRELATION BETWEEN IRI AND RDS								
	STATISTICS OF INDEPENDENT VARIABLES				RANGE OF VALUES			
MODEL	VARIABLE	STANDARD ERROR	t-VALUE	SIGNIF LEVEL OF t-VALUE	MEAN	STD. DEV	MIN	MAX
(a) IRI_{max}	Intercept	0,27089	11,68	0				
	RDS	0,00962	12,09	0	26,39	10,08	10	75
(b) IRI_{avg}	Intercept	0,16753	9,52	0,001				
	RDS	0,05955	12,61	0	26,39	10,08	10	75
INFERENCE SPACE LIMIT FOR IRI_{max} AND IRI_{av}								
IRI_{av}					4,74	1,28	2,72	9,53
IRI_{max}					6,21	2,03	2,8	15,4

- gradient resistance
- horizontal curve resistance.

Whilst all the above resistances are important from an overall pavement design perspective, from the point of view of MMS, the surface characteristics or roughness of the pavement at the point of contact with the vehicle is of primary importance in determining the effect of a change in surface characteristic on performance and costs.

The rolling resistance is the resistance of the pavement surface to the movement of the vehicle and is directly related to the mass of the vehicle. For a specific vehicle type, the major factors which affect rolling resistance are pavement roughness, tyre type and speed (Bester, 1981). Rough surfaces may cause the tyres to;

- slip as a result of low friction
- flex while rolling over rough particles
- climb out of potholes, corrugations etc.
- push through loose material.

Roughness of a pavement surface, which has a wavelength greater than 0,1m is generally accepted as affecting (commercial) vehicle rolling resistance (Shear et al, 1986). The relative movements of vehicle tyre and body are absorbed by the shock absorbers and energy is lost, as is also the case when road roughness induces tyre flexing.

Pavement roughness and the associated rolling resistance is an important consideration in a MMS since numerous researchers (Klamp, 1977 and Hunt et al, 1977) have found that the effect of roughness on overall vehicle operating costs to be significant, these costs being proportional to the forces acting on a vehicle (International Study of Highway Development and Management Tools, ISOHDM, 1995). As most work on rolling resistance and road roughness relationships have been limited to vehicle types commonly used in the public domain, little information exists with regard to the effect of rolling resistance on large ultra-heavy haul trucks. Ideally, the rolling resistance/road roughness relationships required to be developed for this research should incorporate measurements using these vehicles. As a result of the engine and transmission management system limitations of current large haul trucks, no rolling resistance test could be undertaken without excessive modification to the truck management system. In the absence of test results using these trucks, recourse was made to using a standard light commercial vehicle to assess rolling resistance/road roughness relationships. Although the results of this work provides a starting point for the analysis of rolling resistance of mine haul roads, as will be discussed later, the direct application is tenuous. A clear recommendation for future work would be to investigate rolling resistance and pavement roughness attribute effects using the appropriate vehicle.

13.4.1 Analytical Approach to Rolling Resistance Measurement

A number of variables affect the measurement of rolling resistance, including road geometry and roughness, vehicle mass and speed, tyre temperature, type, cold pressure and warm-up times, ambient temperature, wind speed and direction. These are more fully discussed by Bester (1981) and Shear et al (1986). The investigation concentrated on rolling resistance road roughness relationships with speed and extraneous variables not directly related to the study, such as tyre temperature, pressure, warm-up times, etc., being controlled throughout each test.

Pavement rolling resistance was measured by the coast-down technique (Thiene and Dijks, 1981). The vehicle was allowed to coast down in neutral from a number of known constant speeds over a section of road of known geometry and roughness. Roughness was assessed for a number of mine haul road sections exhibiting a wide range of roughness, as determined from the qualitative assessment criteria described in section 13.2. Time and distance travelled during coast-down was recorded together with the constant speed prior to coast-down.

Rolling resistance (expressed as N/kg of vehicle mass) was calculated from both the measured deceleration time and distance, ignoring air drag effects and assuming that the deceleration force was solely attributable to road roughness. Full results are given in Appendix L. Figure 13.5 illustrates a typical example of the results for one particular section of road. These results are broadly similar to those reported by the Institute of

Transportation Engineers (ITE, 1976) for light vehicle travelling on dry well compacted gravel and loose sands, albeit over a lower range of speeds. Six tests were conducted in each direction and the validity of the technique was checked by comparing the derived grade of the test section with the measured grade of the road. The comparisons revealed a variation of 0,1-0,2 grade percent between derived and measured grade and thus established the validity of the results.

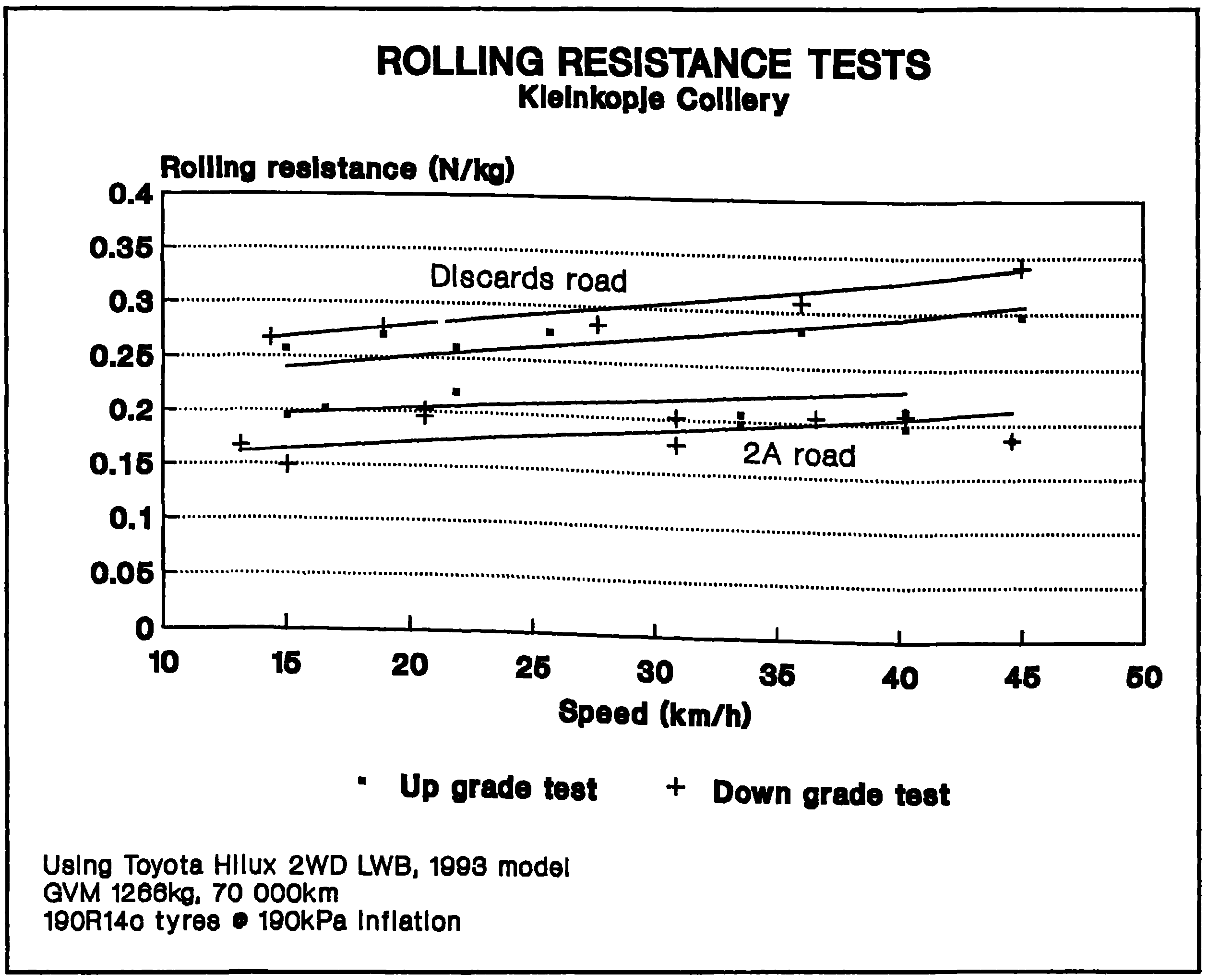


Figure 13.5 Typical results from rolling resistance tests in up- and down-grade directions from two test sections.

13.4.2 Correlation of Rolling Resistance with Roughness Defect Score

The selection of an appropriate model to describe the relationship between roughness defect score (RDS) and rolling resistance (RR) was based on analysis of the RDS for each rolling resistance test section together with corresponding results from the coast-down tests, combined with a theoretical hypothesis of the relationship. The latter was based upon the premise that the rate of rolling resistance increase would decrease at higher levels of RDS. This model is typified by a function having the general form given in Equation [13.2];

$$RR = RRMIN + RDS.\exp^{(f)} \tag{13.2}$$

where

RR	=	Rolling resistance (N/kg)
$RRMIN$	=	Minimum rolling resistance at (RDS)=0
f	=	Regression function describing rate of change in rolling resistance which is a linear combination of independent variables.

Using a logarithmic transformation of the rate of change of rolling resistance (LDRRI), a linear model was developed based on a roughness defect score for the rate of rolling resistance increase. In addition, an expression for the minimum (RRMIN) rolling resistance was sought, based on the independent variable of vehicle speed (V). The major disadvantage of this type of model is that the limit of rolling resistance RRMIN did not fall within the RDS limits of the test sites analysed and recourse had to be made to analysis of the rate of change in rolling resistance at low levels of RDS to determine this value. Equations [13.3] and [13.4] presents the models for RRMIN at RDS=0 and LDRRI.

$$RRMIN = \exp^{(-1{,}7166 + 0{,}0028.V)} \tag{13.3}$$

$$LDRRI = -6{,}368 - 0{,}00685.RDS + 0{,}0061.V \tag{13.4}$$

The model for RRMIN has an R-squared value of 78%, F value of 166,4 which is significant at the 0,1% level for a sample size of 36 and a standard error of the model of 0,191. The model for LDRRI has and R-squared value of 27%, F value of 29,6 which is significant at better than the 2% level for a sample size of 36 and a standard error of 0,146. Full statistics for the models are given in Table 13.4. The full model for rolling resistance variation with roughness defect score is illustrated in Figure 13.6 together with actual data derived from tests at 20, 30 and 40km/h.

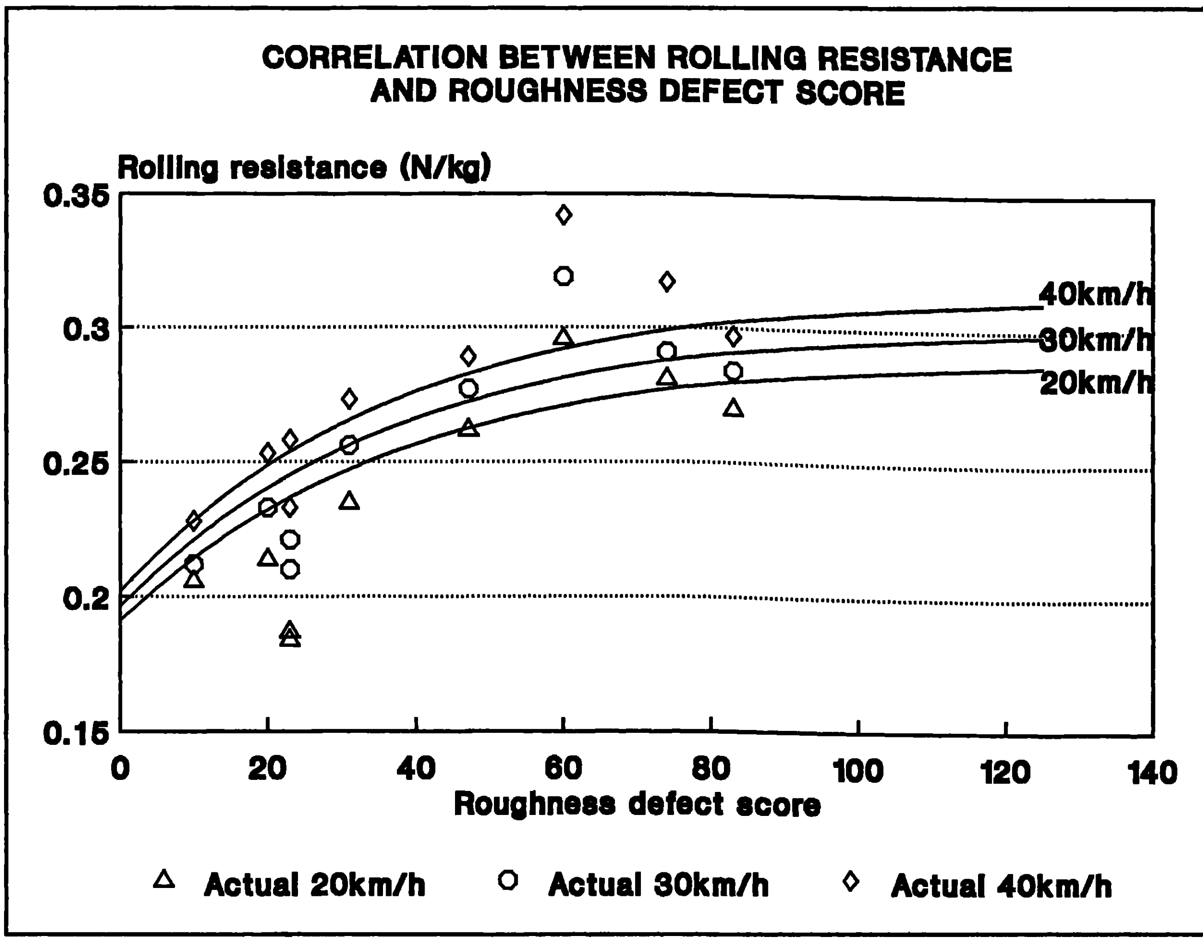


Figure 13.6 Illustration of correlation between actual and model predicted rolling resistance at 20, 30 and 40km/h.

13.4.3 Limits on the Applicability of the Results

In the further development of a MMS where vehicle operating costs are assumed to be related to road roughness and rolling resistance, the use of rolling resistance figures derived from a light four wheeled vehicle with a GVM of 1,266t, tyre pressures of 190kPa and tyre diameter of 0,8m cannot be assumed to reflect the rolling resistance experienced by six wheeled hauler of some 300t GVM at tyre pressures of 640kPa and a tyre diameter in

Table 13.4 Rolling Resistance and Roughness Defect Score Correlation Model Statistics

STATISTICS OF MODEL ESTIMATION FOR RR AND RDS								
	STATISTICS OF INDEPENDENT VARIABLES				RANGE OF VALUES			
MODEL	VARIABLE	STANDARD ERROR	t-VALUE	SIGNIF LEVEL OF t-VALUE	MEAN	STD. DEV	MIN	MAX
1 RRMIN	Intercept	0,06093	-37,54	0	-	-	-	-
	V	0,00146	8,76	0,0001	18,51	17,58	12	30
2 LDRRI	Intercept	0,04396	-15,88	0	-	-	-	-
	RDS	0,00751	13,67	0	31,35	20,67	14	74
	V	0,00061	8,43	0,004	28,48	13,26	12	72

excess of 1,9m. Even in the case of a comparison between small motor cars and heavy articulated trucks it has been shown that the speed associated increase in rolling resistance is absent in trucks (Gyenes, 1978). Numerous other factors are also identified which suggest heavier vehicles experience lower rolling resistance over the same section of road as would lighter cars by virtue of different tyre diameters and types (Wong, 1993) and inflation pressures (Thiene and Dijks, 1981) which reduces the hysteresis loss on larger tyres. These effects are typified by the coefficient of rolling resistance (CR) values adopted in HDM-III (Watanatada et al, 1987) where;

$$CR = 0{,}0128 + 0{,}00061.IRI \qquad (13.5)$$

represents the coefficient of rolling resistance for cars and light commercial vehicles and

$$CR = 0{,}0139 + 0.00026.IRI \qquad (13.6)$$

represents the coefficient of rolling resistance for buses and heavy commercial vehicles, based on paved and unpaved roads roughness values of 2,23 to 13,69 IRI.

Du Plessis (1990) proposed a model for the static coefficient of rolling resistance (CR_0) which used roughness and tyre pressure as independent variables. Substituting a tyre pressure of 640kPa gives the following relationship;

$$CR_o \approx 0,00874 + 0,00043.IRI \qquad (13.7)$$

These various relationships are plotted in Figure 13.7 in relation to the rolling resistance data generated for mine haul roads at corresponding levels of standard (average) IRI roughness calculated from Equation [13.1b]. It is evident that the model is broadly similar to the coefficients of rolling resistance experienced by light commercial vehicles (LCV), although the rate of change in rolling resistance with IRI is not constant as with the other models. The form of the model suggests a decreasing rate of rolling resistance increase, the majority of the increase in rolling roughness taking place between IRI=3,0 and IRI=6, implying that rolling resistance will eventually reach a maximum value irrespective of further increases in IRI roughness.

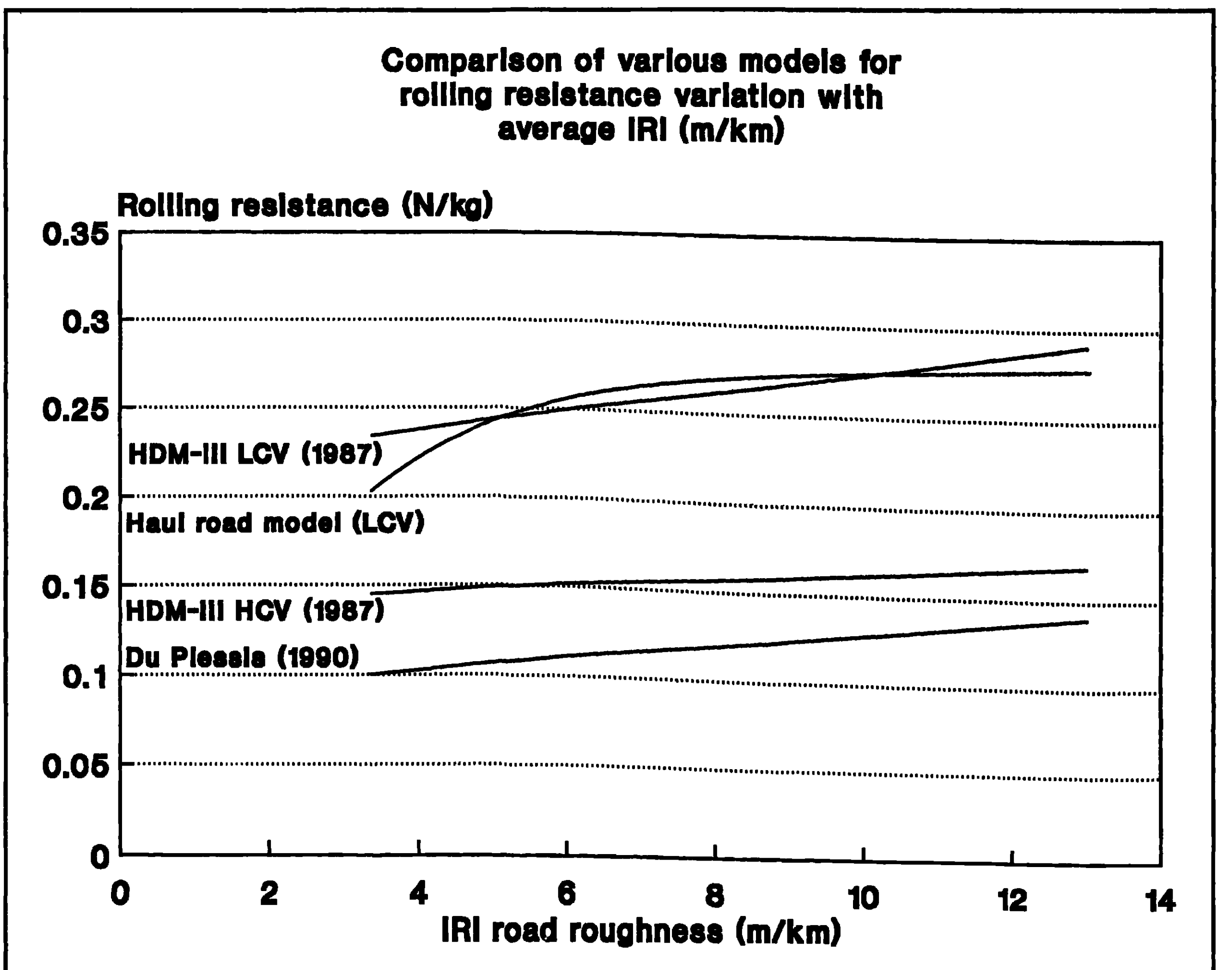


Figure 13.7 Comparison between models of coefficient of rolling resistance increase with IRI roughness.

Whilst it is possible to motivate a general decrease in reported rolling resistance values to simulate more closely the results of heavy commercial vehicles, based on the data presented in Figure 13.7, there remains a considerable difference between these vehicles and haul trucks in terms of the influence of surface roughness, especially in regard to the road deformation characteristics of soft road surfaces under the action of ultra-high axle loads.

One of the major warrants for the development of a qualitative road roughness assessment methodology was in response to the hitherto localised and subjective nature of road roughness reporting as discussed in Chapter 2. In this regard, the typical rolling resistances and haul road descriptions given in Table 2.3 were seen to be subject to differing interpretation and did not fully address the contributory components of haul road roughness. Nevertheless, they can be used as a tentative first estimation as to the likely over-or under-estimation of rolling resistance associated with the current tests. Category I and II roads in Table 2.3 correspond closely to the general roughness conditions and maintenance activities applicable to the rolling resistance test sections. In addition, in Chapter 5.5 it was shown that the weakest haul road structure was associated with a maximum deflection of 7mm. These facts appear to confirm the selection of category II as the typical upper limit to haul road roughness. Rolling resistance is accordingly reported to vary from a lower limit 0,196 to an upper limit of 0,318 N/kg as given in Table 2.3 (after Caterpillar, 1990). A dynamic coefficient of rolling resistance is also reported by Caterpillar (1993) of 156x10^{-6}N/kg/km/h for large haul trucks. This speed dependant effect, although not well understood and poorly determined at present is thought to be associated with tyre deflection and motion resistance effects at speed (Diack, 1996).

Whilst the category II rolling resistance limits are coincidently similar to the values generated during the current testwork, they are considerably higher than those reported for heavy commercial vehicles. It may be hypothesised that the combination of larger tyres and GVM gives rise to greater tyre flexing and hysteresis. Tyres contact are is also considerably larger and thus the resistance effects of road roughness may be larger, although the areal extent of the contributory components of roughness would also be correspondingly larger.

Based on the tentative similarity between experimentally derived rolling resistance model values for mine haul road roughness and those reported in the literature (although of obscure derivation) it is proposed that the models derived to describe rolling resistance variation with road roughness be provisionally adopted in the MMS model, subject to more applicable data becoming available.

13.5 Road Roughness Progression Model

The analytical approach to measuring roughness in terms of both the qualitative five-point assessment of individual sections of road and the correlation with rolling resistance was described in section 13.2 in which the pavement defects of potholing, corrugation, rutting, loose material and fixed stoniness were used to describe road roughness. The approach adopted in the development of a road roughness progression model involved the analysis of these roughness defects in conjunction with mine site material property and traffic volume data. The functionality assessment data (Chapter 9 and Appendix F) was reanalysed in terms of those defects contributing to road roughness, from which individual defect progressions and an overall progression rate was determined.

A schematic roughness defect score progression is illustrated in Figure 13.8, repeated over two maintenance cycles from which two distinct traffic and material induced actions can be hypothesised. Following maintenance there is an increase in defect score due initially to the displacement of loose material, followed by an increase in dynamic loadings imposed on the road together with an increase in abrasion. This causes an accelerating rate of progression until traffic speed slows and wheel paths change to avoid damaged sections. At this level of defect the progression rate will decelerate to an eventual static level beyond which no further increase in score is seen.

This model differs from the functional defect progression model by virtue of the type of defects analysed. The initially decreasing defect score is eliminated since only loose material exhibits a traffic induced reduction in defect score following maintenance, the remaining defects obscuring this isolated post-maintenance decrease. This effect is typically illustrated in Figure 13.9 in which the decreasing loose material defect score and the increasing pothole,

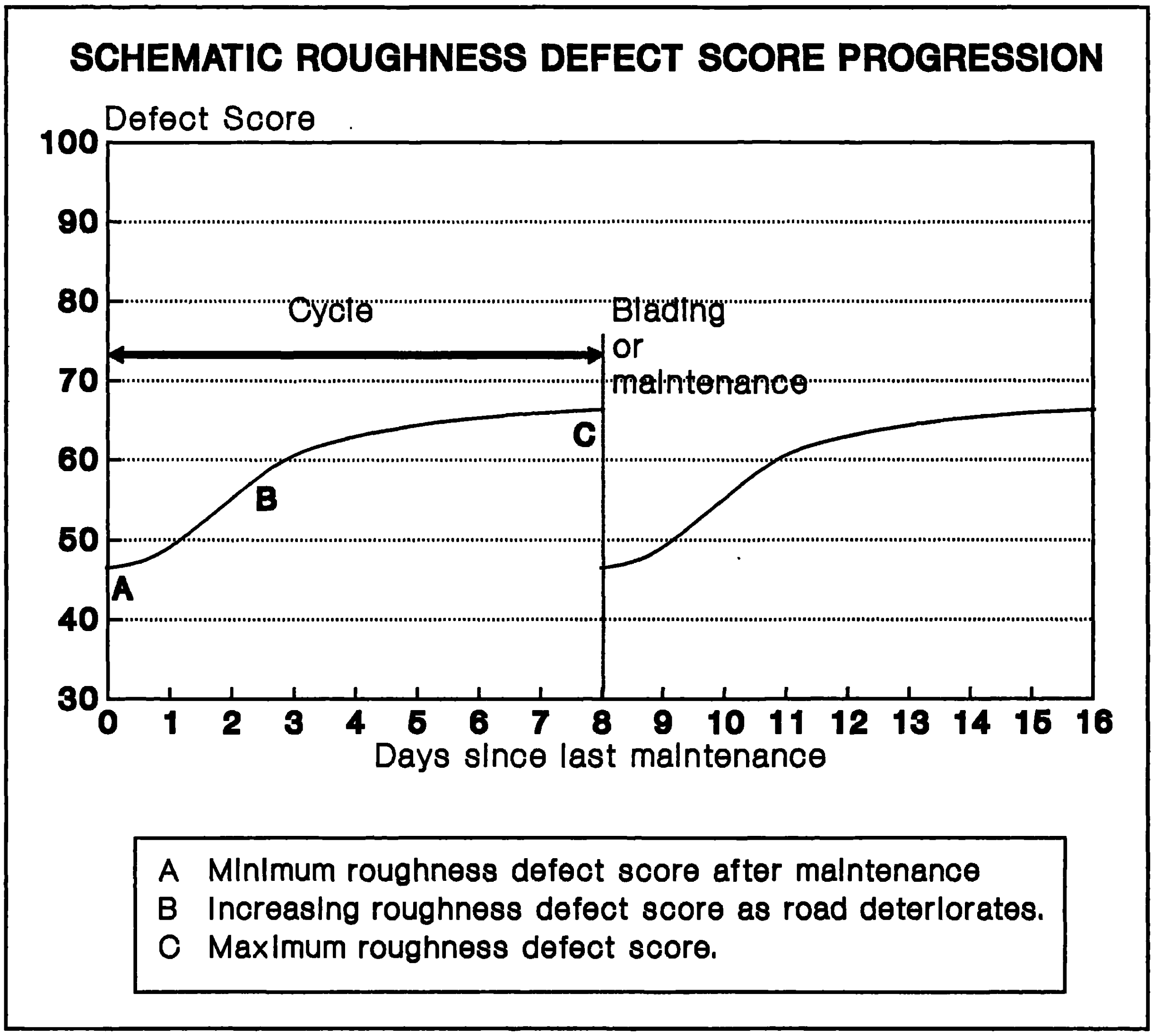


Figure 13.8 Schematic illustration of roughness defect score model.

corrugation and rutting scores are seen. As regards fixed stoniness, very little variation was seen in this defect score over the maintenance intervals analysed, although it may be anticipated that as abrasion and material whip-off increases, more large stones would become apparent in the wearing course.

The selection of a model for roughness defect score progression was based on the aforementioned vehicle and pavement interactions in which a decreasing rate of defect score increase was assumed. This has the general form of;

$$RDS = RDSMIN + \left[\frac{RDSMAX - RDSMIN}{1 + \exp^{(D.f)}}\right] \tag{13.8}$$

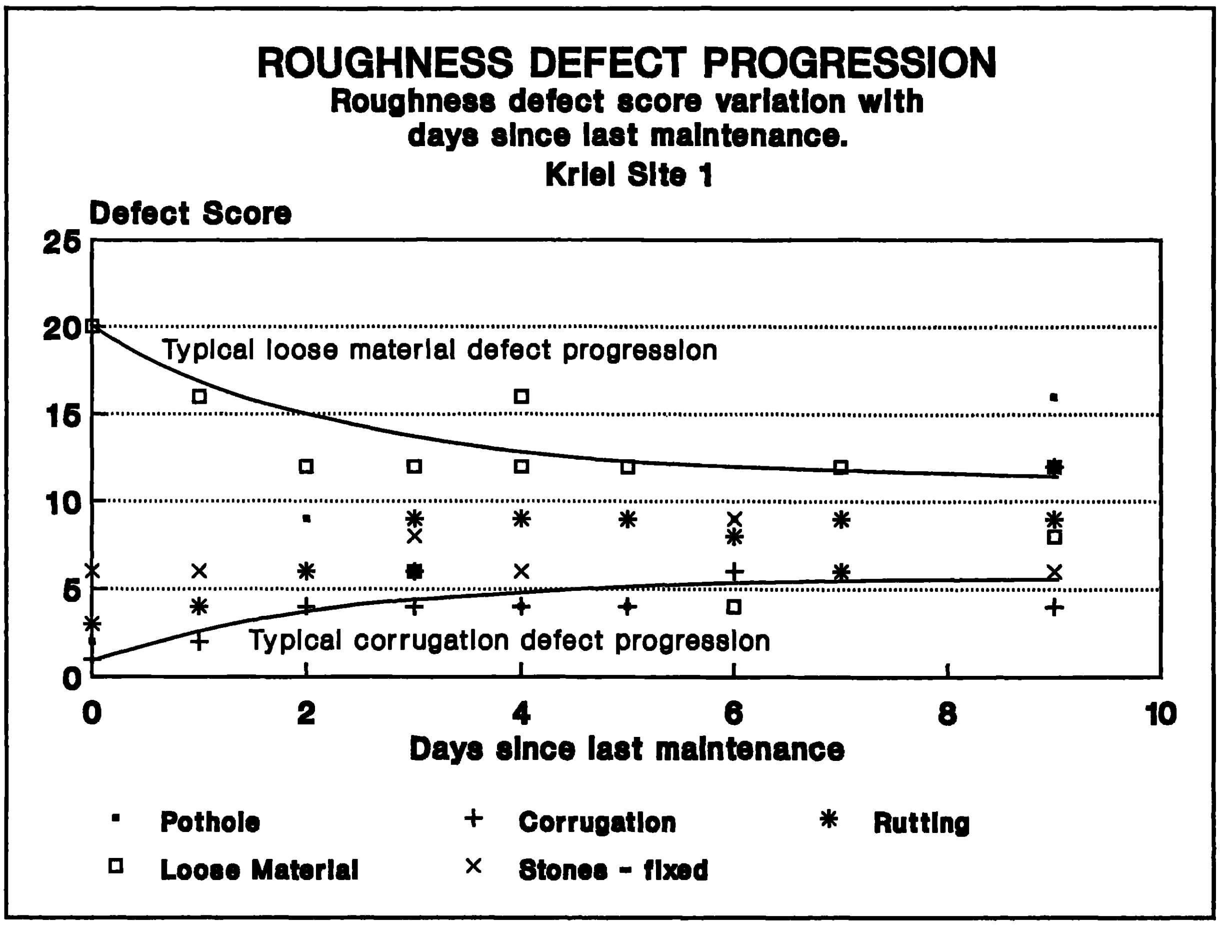


Figure 13.9 Typical individual roughness defect component score progressions.

where

RDS	=	Roughness defect score
RDSMIN	=	Minimum roughness defect score at time (*D*)=0
RDSMAX	=	Maximum defect score
f	=	Regression function which is a linear combination of independent variables.

Using a logarithmic transformation of roughness defect scores, a defect progression model was developed based on a linear combination of the independent variables for the rate of roughness defect score increase (LDRDI). In addition, expressions for the minimum (RDSMIN) and maximum (RDSMAX) roughness defect scores were sought, both assumed to be linear combinations of the independent variables as illustrated in Figure 13.10.

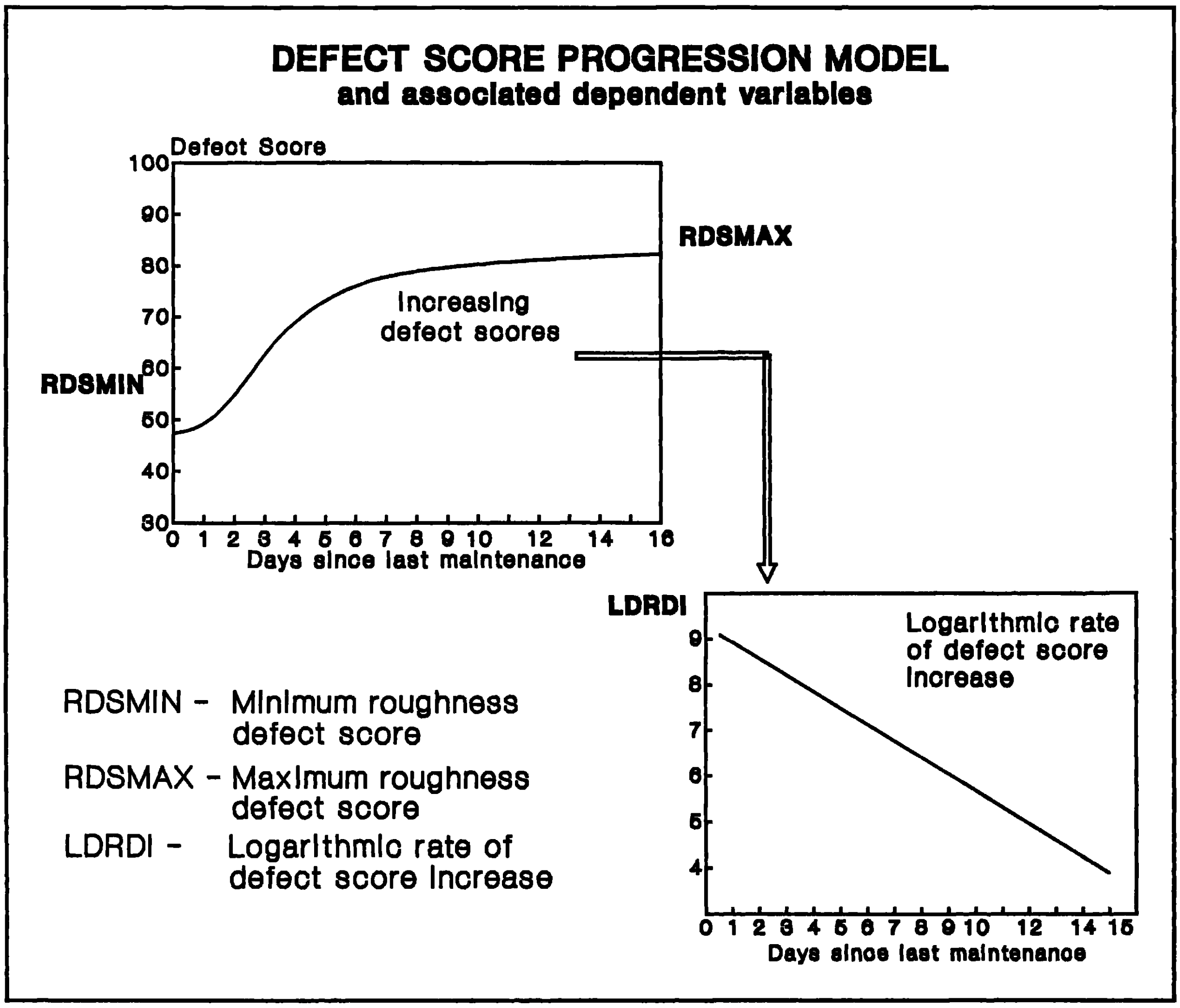


Figure 13.10 Selection of model and dependant variables for roughness defect score progression.

The rate of change in roughness defect scores was calculated over a single maintenance cycle in terms of LDRDI and these values used as the dependant variables in a multiple correlation analysis in order to determine the significant factors affecting defect score progression. Table 10.1 gives the independent variables and their definitions as used in the regression analysis. For the exponential model of rate of roughness defect score increase after maintenance, the model given in Equation [13.9] was found to be significant:

$$LDRDI = 1{,}768 + 0{,}001.D(2{,}69.KT - 72{,}75.PI - 2{,}59.CBR - 9{,}35.GC + 1{,}67.SP) \quad (13.9)$$

The model has an R-squared value of 52%, F value of 13,8 which is significant at better than the 1% level for a sample size of 59. For the standard error of the model of 0,589, the approximate 95% confidence intervals for a rate of change of in defect score increase of 6 per unit time lie between 1,84 and 19,48. The goodness of fit between observed and predicted rates of increase is illustrated in Figure 13.11 and full statistics for the model are given in Table 13.5 from which it seen that although the inclusion of daily tonnage (D.KT) is not significant in the regression it is nevertheless included to accomodate an envisaged increase in roughness defect score with increased traffic. Equation [13.9] predicts an increase in the rate of roughness defect score progression for increasing traffic volumes (KT), material grading coefficient (GC) and shrinkage product (SP). The material properties of CBR and plasticity index (PI) are associated with a reduced rate of increase. As discussed in Chapter 10, the material properties associated with plasticity (in this case SP and PI) are more likely to be associated with an increasing rate of progression. Whilst no multi-collinearity was evident to explain this contradiction in the independent variables it may be hypothesised that whilst highly plastic materials are associated with increasing progression rates (especially if wet), relatively low values of plasticity could result in a decreasing rate (increasing plasticity improving binding up to a point) as evidenced here. The remaining independent variables confirm the thesis adopted earlier. Figure 13.12 illustrates the effect of increasing traffic volume (kt per day) on the roughness defect score progression rate for one particular set of material property and minimum and maximum defect score values.

To establish the minimum roughness defect score immediately after maintenance an analysis was conducted using RDSMIN as the dependant variable. The regression rendered the model given in Equation [13.10];

$$RDSMIN = 31{,}1919 - 0{,}05354.SP - 0{,}0152.CBR \qquad (13.10)$$

The model has an R-squared value of 62%, F value of 12,6 which is significant at better than the 1% level for a sample size of 9. For the standard error of the model of 1,73, the approximate 95% confidence intervals for a minimum defect score of 25 lie between 21,54 and 28,46. Full statistics for the model are given in Table 13.5. From the model it is seen

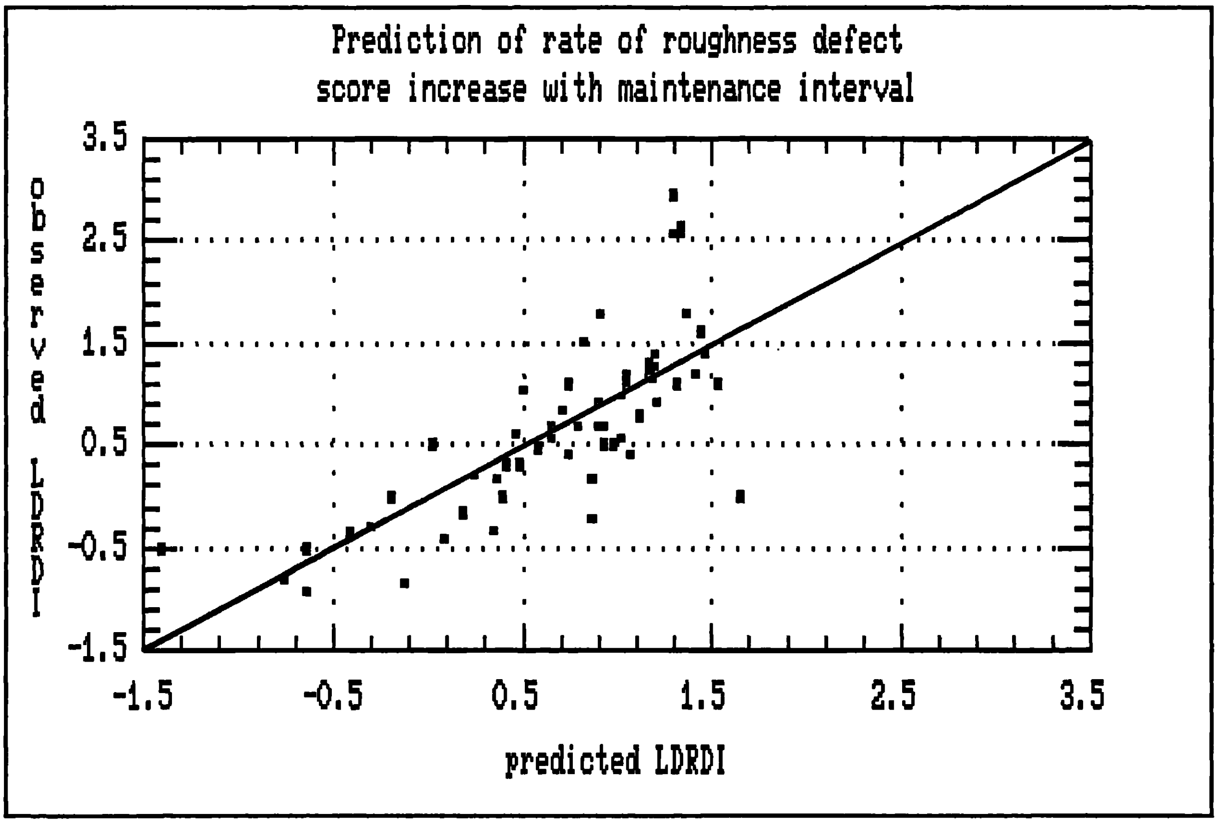


Figure 13.11 Goodness of fit for model of LDRDI.

that increasing CBR values result in a lower minimum roughness defect score. The material shrinkage product (SP) also results in a lower minimum score, most probably due to a better surface being produced immediately after maintenance as a result of a more plastic and finer grained wearing course material. Whilst it may be hypothesised that traffic volume may result in a higher minimum defect score due to excessive maximum roughness, the converse has also been observed where higher traffic volumes produce a more compact wearing course than is seen on similar roads subject to lower traffic volumes. This result also implies that maintenance temporarily eradicates all traffic induced roughness defects, hence the prediction of minimum defect score as being a function only of material properties appears reasonable.

The model for maximum roughness defect score is given below in Equation [13.11];

$$RDSMAX = 7{,}6415 + 0{,}4214.KT + 0{,}3133.GC + 0{,}4952.RDSMIN \qquad (13.11)$$

The model has an R-squared value of 90%, F value of 22,9 which is significant at better than

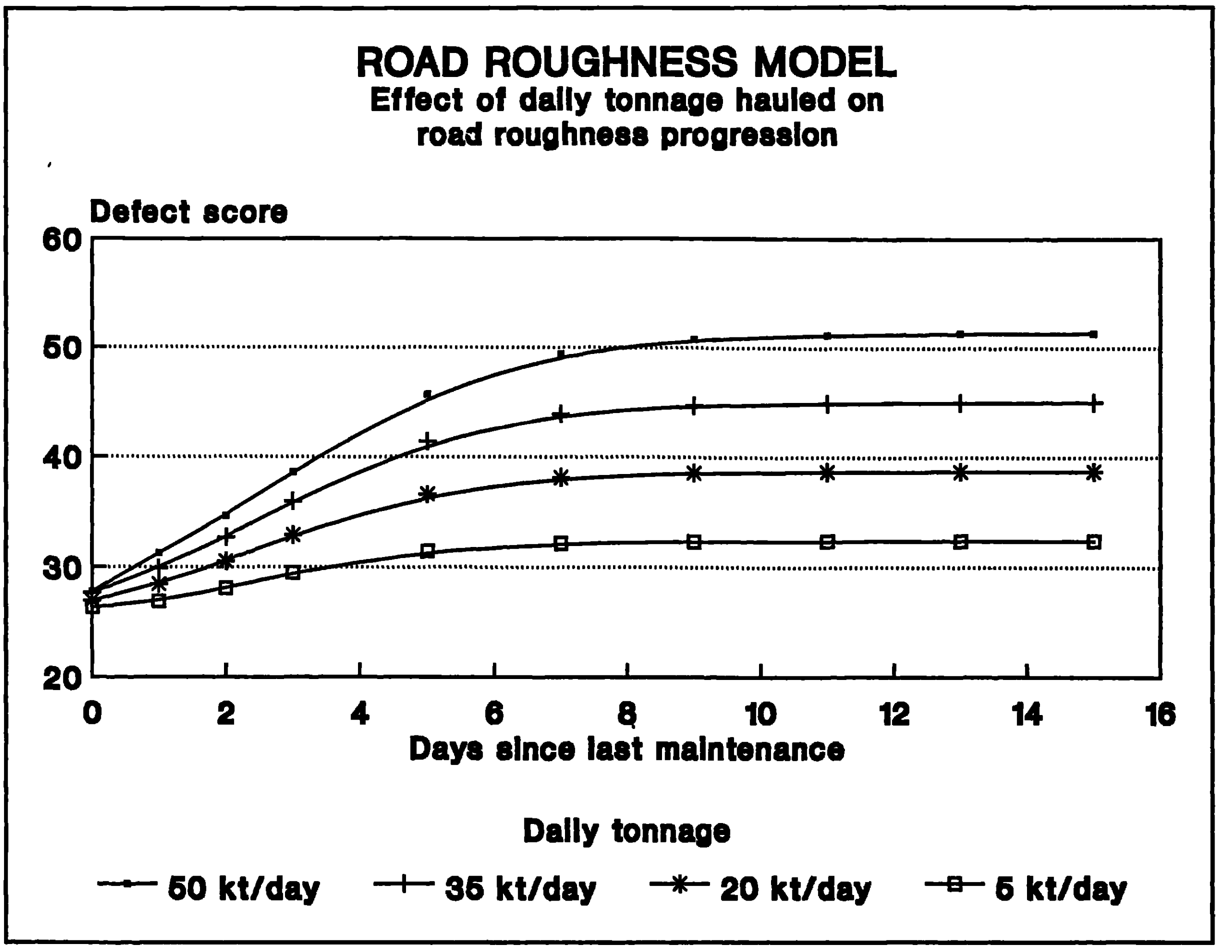


Figure 13.12 Effect of increasing daily tonnage on roughness defect score progression.

the 0,5% level for a sample size of 9. For the standard error of the model of 1,34, the approximate 95% confidence intervals for a minimum defect score of 35 lie between 32,32 and 37,68. Full statistics for the model are given in Table 13.5 from which it is seen that the intercept value, although not significant in the regression, is necessary for the correct form of model hypothesised. From the model it is seen that increasing daily tonnage (KT) representing more accumulated damage, grading coefficient (GC) representing deficiencies in binder material (hence corrugation and ravelling) and minimum defect score all increase the maximum defect score.

When applied to a typical mine site, the models reflect closely the actual roughness defect scores recorded as shown in Figure 13.13. Full comparative results are given in Appendix M. When these defect scores are converted into rolling resistance values following Equations [13.3 and 4] it is seen that over a maintenance interval in excess of 9 days rolling resistance increases from 0,263N/kg to 0,284N/kg at this particular site, equivalent to an additional 0,2% grade resistance. Over a haul road, this increase in rolling resistance can be directly associated with an increase in vehicle operating costs once a vehicle operating cost model is established.

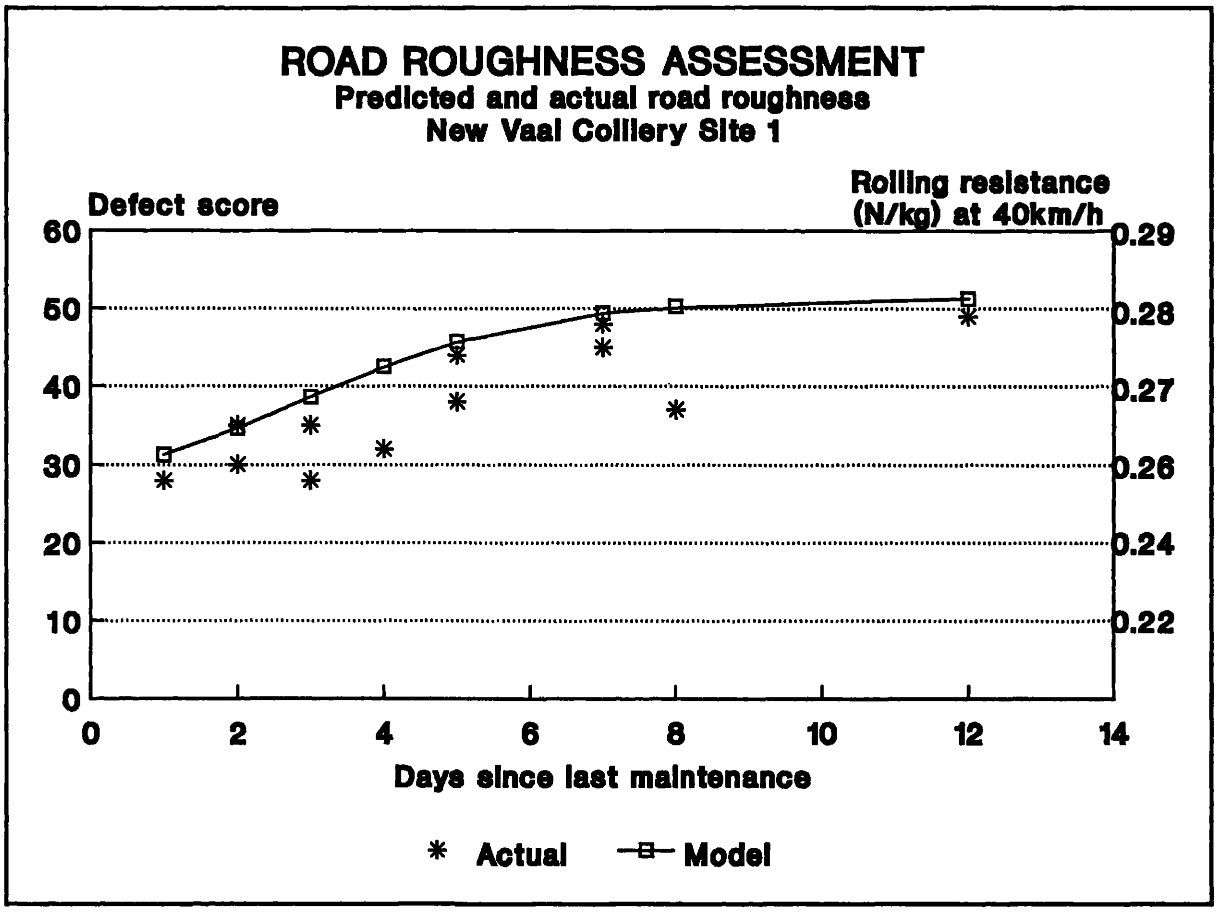


Figure 13.13 Estimation characteristics of prediction model for roughness progression as applied at New Vaal Colliery site 1.

13.6 Summary and Conclusions

A qualitative road roughness evaluation technique was developed as a precursor to the development of a model for roughness progression which forms the basis of the MMS model. The adoption of roughness defect results for pothole, corrugation, rutting, loose material and fixed stoniness from functional monitoring over a 12 month period enabled such a model to be developed based on a maintenance interval of between 1 and 19 days. 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

Table 13.5 Roughness Defect Score Progression Model Statistics

STATISTICS OF MODEL ESTIMATION FOR LDRDI, RDSMIN AND RDSMAX								
	STATISTICS OF INDEPENDENT VARIABLES				RANGE OF VALUES			
MODEL	VARIABLE	STANDARD ERROR	t-VALUE	SIGNIF LEVEL OF t-VALUE	MEAN	STD. DEV	MIN	MAX
1 LDRDI	Intercept	0,18161	9,70	0	-	-	-	-
	D.KT	0,00118	1,40	0,1	110,45	116,63	15	600
	D.PI	0,01734	-4,19	0,0001	45,38	27,06	4	128
	D.CBR	0,00062	-4,17	0,0001	484,83	279,7	92	1274
	D.GC	0,00403	2,31	0,024	181,3	89,2	24,8	459,2
	D.SP	0,00056	2,94	0,01	962,6	605,5	102	2744
2 RDSMIN	Intercept	2,28071	14,99	0	-	-	-	-
	SP	0,01504	-3,55	0,012	-	-	-	-
	CBR	0,01014	-2,72	0,019	-	-	-	-
3 RDSMX	Intercept	7,66929	1,38	0,23	-	-	-	-
	KT	0,04044	5,47	0,05	-	-	-	-
	GC	0,13532	2,31	0,08	-	-	-	-
	RDSMIN	0,20752	2,38	0,07	22,17	1,91	19,9	24.9
INFERENCE SPACE LIMITS FOR INDEPENDENT VARIABLES USED IN MODEL (1) TO (3)								
KT					16,85	12,59	6,0	50,0
PI					7,03	1,85	4	10
CBR					78,89	29,42	46,3	132
GC					28,96	4,54	21,3	36,3
SP					149,24	41,27	90	198,0
D					6,2	4,39	1	19

decreasing progression.

To facilitate portability and comparison of the qualitative assessment technique, the qualitative road roughness was compared to the IRI roughness. Expressions were developed to enable direct comparison to be made between roughness defect score and IRI. 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 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. Based on the tentative similarity between experimentally derived rolling resistance model values for mine haul road roughness and those reported in the literature it was proposed that the models derived to describe rolling resistance variation with road roughness be provisionally adopted in the MMS model. However, to fully characterise the effect of road roughness attributes on ultra-heavy haul trucks it is recommended that an investigation be undertaken specifically using these trucks since the direct application of the data is nevertheless tenuous.

CHAPTER 14
VEHICLE OPERATING AND ROAD MAINTENANCE COST MODELS

14.1 Introduction

The second element of a MMS for mine haul roads is based on models of the variation of vehicle operating costs with road roughness. A road roughness progression model was developed in the previous chapter to explain the variation in road roughness or rolling resistance with time or tonnage hauled. This chapter addresses the development of vehicle operating cost prediction models for fuel consumption, tyre cost and vehicle (parts and labour) costs with increased rolling resistance of a haul road. Table 3.14 lists the various model data requirements whilst Figure 2.12 illustrates the concept of vehicle operating cost variation with road roughness. When combined with the road maintenance cost model developed later in the chapter, the optimal maintenance strategy for a specific mine haul road, commensurate with lowest overall vehicle and road maintenance costs may be identified.

14.2 Fuel Consumption Model

The prediction of fuel consumption variation with road roughness is central to any MMS and fuel consumption itself is a significant component of total vehicle operating costs. Fuel consumption of vehicles in the public domain has been shown to vary with vehicle type and speed, road curvature, traffic volume and the grade of the road (Chesher and Harrison, 1987). A description of the analytical approach adopted in determining the contribution of these various factors to haul truck vehicle fuel consumption is described.

14.2.1 Analytical Approach

The analytical approach adopted in the determination of haul truck fuel consumption involved the computer simulation of specific haul trucks to generate a speed model for a range of vehicles commonly used for coal haulage. The speed model formed the basis of the fuel consumption model which was derived from vehicle simulations coupled with vehicle torque/fuel consumption maps. The models developed are finally tested in comparison to mine site vehicle fuel consumption and average journey time data.

The vehicles chosen for the simulation exercises incorporated five rear-dump coal haul trucks typical of the vehicles employed on strip coal mines for coal hauling. Table 14.1 presents a summary of the simulation fleet parameters and Appendix N full vehicle specifications.

Table 14.1 Simulation Vehicle Fleet Specifications

Haul Truck Type	**Manufacturer**	**Fuel and Drive**	**Engine Type**	**Engine Torque (kN) @rpm**	**Tyre Type**	**Gross Vehicle Mass (GVM) (t)**	**Unladen Vehicle Mass (UVM) (t)**
CAT789	Caterpillar	D TC/DD M	Cat3516	1244 @1900	3600R51	274	120
CAT785	Caterpillar	D TC/DD M	Cat3512	1013 @1900	3000R51	219	95
R170	Euclid	D E	Cummins KTA 50C	1193 @1900	3600R51	274	120
630EH	Dresser-Haulpak	D E	Detroit 16V-149T1B	1342 @1900	3700R57	277	114
CAT793	Caterpillar	D TC/DD M	Cat3516	1487 @1900	4000R57	362	144

Notes

D	Diesel fuel
TC	Torque converter drive up to 7-8km/h
DD	Direct drive with torque converter lock-up above 7-8km/h
M	Mechanical drive
E	Electric drive (electric rear wheel motors)

The vehicle types chosen for the assessment may be classified in terms of gross power (kW) to GVM and UVM ratios from 4,4-4,9 and 11,1-11,8 respectively. Both electric and mechanical drive options have been analysed although the recent trend is to mechanical drive for the larger haul trucks (Caterpillar, 1993). These trucks are referred to in the following analysis with the exception of the R170 which is seen to be similar to the 630EH truck.

The simulation exercises were run on the Komatsu Optimum Fleet Recommendation package (Komatsu, 1994). This simulation package incorporates engine torque/fuel consumption maps for each vehicle and engine combination chosen, together with a vehicle speed/rimpull map and torque/speed ratio map for the particular drive configuration adopted. Vehicle speed limitations on favourable (down) grades are limited by the particular retarder option chosen which is described by a retarder force/speed limit/distance map.

14.2.2 Vehicle Speed Model

As a precursor to the vehicle fuel consumption model, a model was developed to describe the speed variation of haul trucks with total resistance. Total resistance is defined as the sum of rolling and grade resistances as given in Equation [14.1]. Rolling resistance is described as a percentage of vehicle mass as given in Equation [14.2] and grade similarly in terms of percentage meters rise (+) or fall (-) per meter.

$$TR(\%) = GR(\%) + RR(\%) \qquad (14.1)$$

Where

TR	=	Total rolling resistance (%)
GR(%)	=	Grade resistance (%)
RR(%)	=	Rolling resistance (%)

and

$$RR(\%) = \frac{RR.100}{g} \qquad (14.2)$$

where

RR = Rolling resistance (N/kg)

g = acceleration due to gravity, 9,81m/s^2

and

$$GR(\%) = \frac{GR.100}{g} \tag{14.3}$$

where

GR = Grade resistance (N/kg)

Simulations were conducted with the vehicles given in Table 14.1 for both laden and unladen conditions over a range of favourable and unfavourable grades of road. The simulation model comprised a number of road sections interspersed with shorter acceleration sections such that a constant velocity was attained over alternate road sections. Vehicle speeds were unlimited on both grades. As can be seen from Figures 14.1 and 14.2, two distinct grade/velocity profiles are seen for both favourable and unfavourable grades. For favourable grades with unladen trucks, the vehicle retarder limits the vehicle speed to approximately 55km/h between total resistance values of 0 and -8%. At higher values, vehicle speed is limited by the safe speed of the vehicle in conjunction with retarder performance and thus reduces slightly. A similar effect is seen for laden trucks, the constant speed retarder controlled section being smaller due to increased weight of the truck and its propensity to accelerate down-grade to a speed beyond the limits of vehicle braking.

The profiles of speed against unfavourable grade show similar characteristics, the laden vehicles losing speed more rapidly as the unladen vehicles. In all cases a logit function of the general form given below in Equation [14.4] is used to model the variation in speed for favourable grades laden and unladen (VFL and VFUL respectively) and unfavourable grades laden and unladen (VUFL and VUFUL respectively) with total resistance (TR).

$$V = VMIN + \left[\frac{VMAX - VMIN}{1 + \exp^{(f)}}\right] \tag{14.4}$$

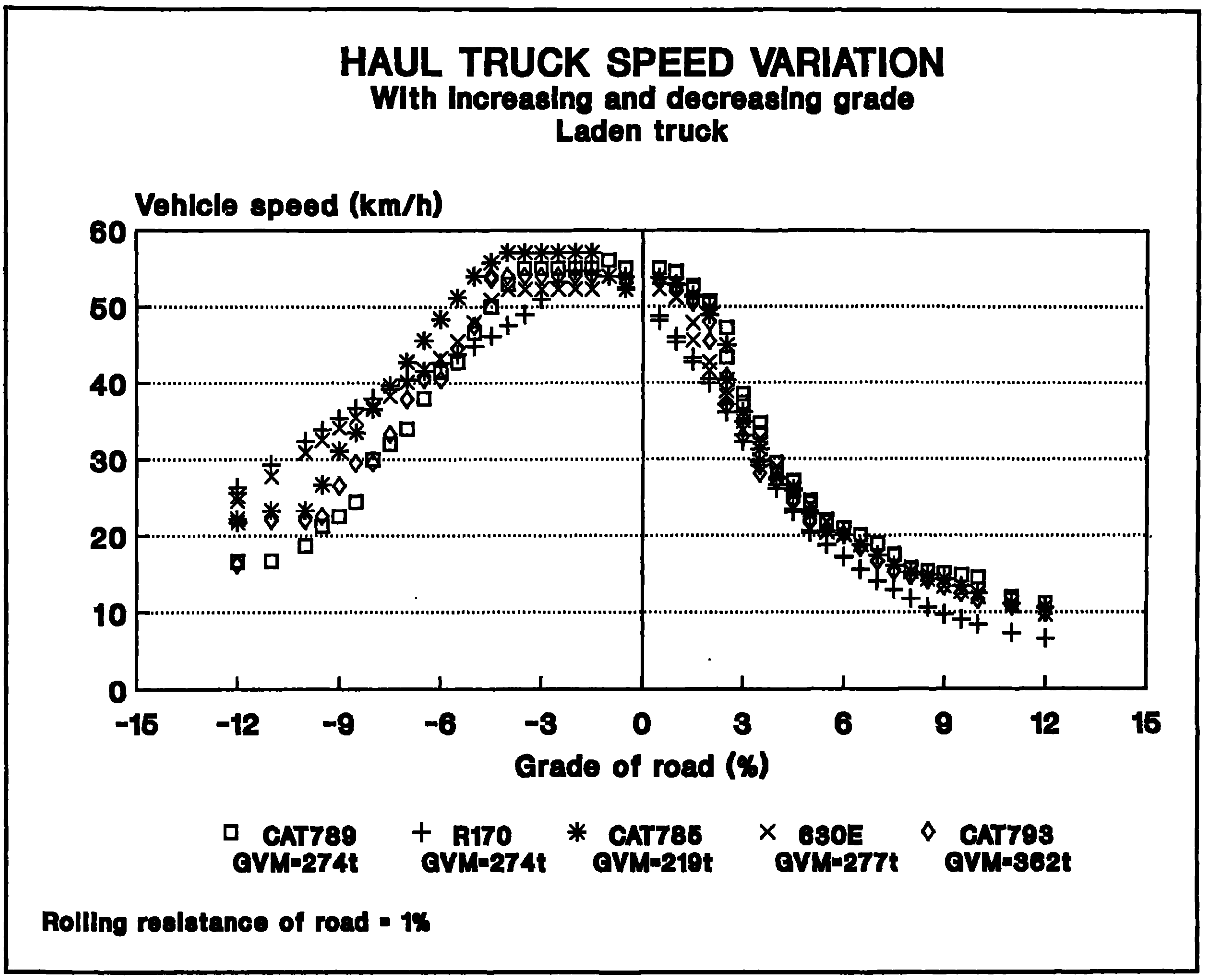


Figure 14.1 Haul truck speed variation for laden simulation fleet.

where

V	=	Vehicle speed (km/h)
$VMIN$	=	Minimum vehicle speed (km/h)
$VMAX$	=	Maximum vehicle speed (km/h)
f	=	Regression function which is linear in total resistance (TR)

The limits of VMIN and VMAX were calculated from inspection of the data combined for all truck types simulated and the following speed models accordingly derived:

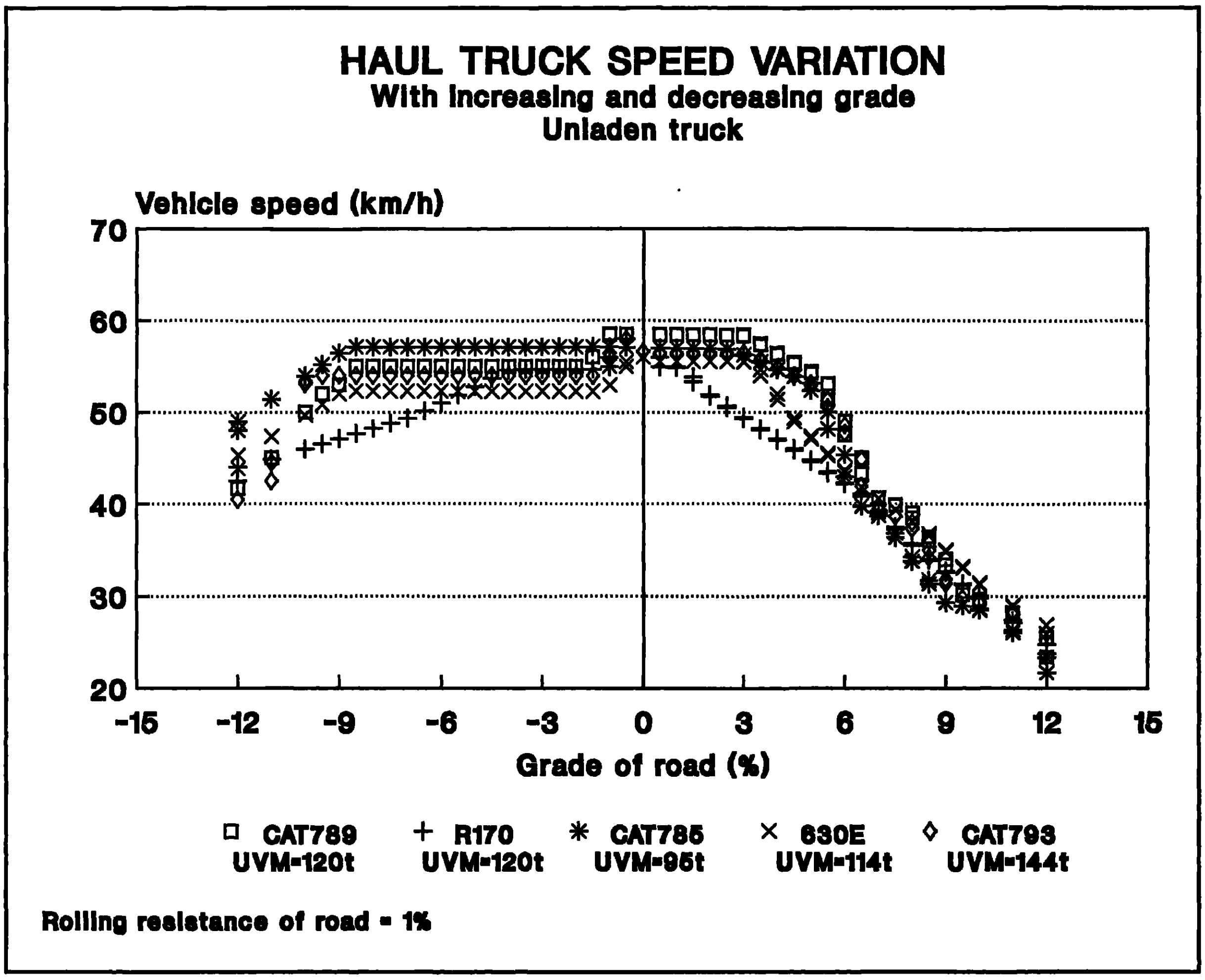


Figure 14.2 Haul truck speed variation for unladen simulation fleet.

$$VFU = 13 + \left[\frac{42}{1+\exp^{\left(\frac{TR+10,03}{-0,803}\right)}}\right] \tag{14.5}$$

$$VUFU = 22 + \left[\frac{36}{1+\exp^{\left(\frac{TR-6,31}{1,9}\right)}}\right] \tag{14.6}$$

$$VFL = 5 + \left[\frac{49}{1+\exp^{\left(\frac{TR+9,5}{-2,4}\right)}}\right] \tag{14.7}$$

$$VUFL = 9 + \left[\frac{55}{1+\exp^{\left(\frac{TR-2,25}{1,75}\right)}} \right] \tag{14.8}$$

The combined models are shown in Figure 14.3 plotted against total favourable and unfavourable resistance for both unladen and laden trucks. The simulation assumes no traffic interference (from slower moving vehicles) or congestion. The effect of curvature on vehicle speed and total resistance was also investigated by means of specifying the radius of curvature of the sections of haul road comprising the model. For the common limits of haul road geometric design, curvature values of 10° to 90° per 1000m did not reveal any significant decrease in speed. This is due to the much lower super-elevation adopted in the design of mine haul roads, commensurate with the lower vehicle speeds, than those values adopted for the design of public paved and unpaved roads. Some reduction in speed is nevertheless a requirement for safe operation, but this is only applicable for speeds in excess of 48km/h on bends of radii of less than 60m which generally lies outside the range of geometric designs encountered. The effect of air resistance on total resistance, although varying proportionally to the square of the vehicle velocity, was ignored for in this analysis due to the relatively low vehicle speeds and similar frontal areas of the simulation vehicles (Caterpillar, 1993).

14.2.3 Constant Speed Fuel Consumption

The development of a constant speed fuel consumption model utilised the Komatsu OFR simulation program as described previously, in this case using a set course comprising of acceleration and constant speed sections with differing maximum speed limits applied. The course was modelled with various total resistance (TR%) values from -10 to 10%. The dynamic rolling resistance was modelled following Caterpillar (1993) as described in Chapter 13. Figures 14.4 and 14.5 illustrate the variation in fuel consumption with vehicle speed for a laden and unladen Cat 789 vehicle as described in section 14.2.2 running against an (unfavourable) total resistances of 0 and 6%. The curves are broadly similar to those reported for heavy commercial vehicles. Where TR=0%, a slightly increasing rate of fuel

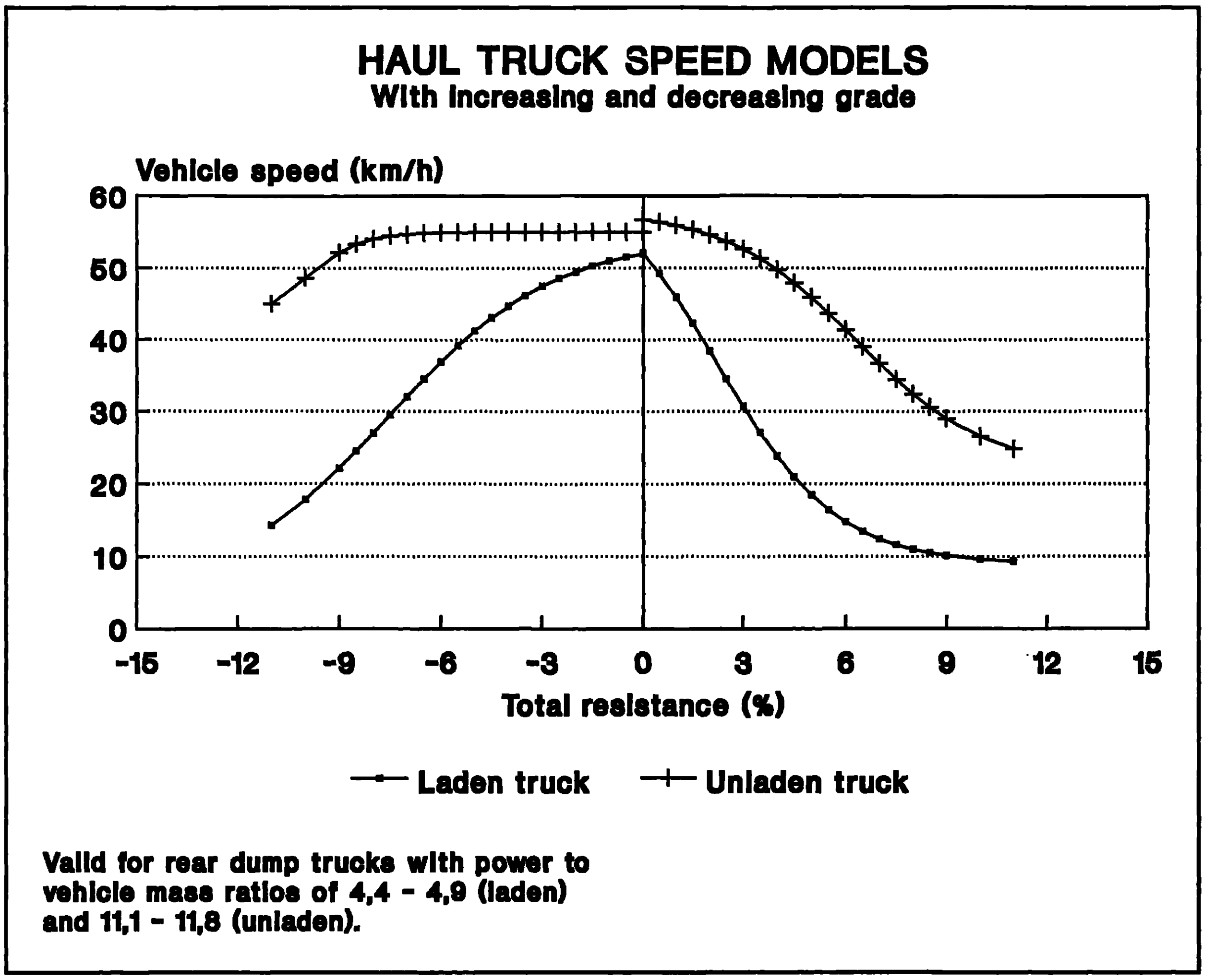


Figure 14.3 Combined speed models for laden and unladen trucks.

consumption with speed is seen due to dynamic rolling resistance effects. At higher levels of total resistance this effect is largely obscured by the approximately linear increase in fuel consumption with speed. A similar effect can be hypothesised from work presented by Chesher and Harrison (1987) in which the rate of fuel consumption increase with speed for heavier vehicles (albeit from various studies) appears less than for light vehicles and motor cars. There is some evidence of increased fuel consumption at low speeds and low total resistance values due to the effect of torque converter drive being engaged at low speeds (7-8km/h). This effect becomes progressively less evident as total resistance increases and as such was ignored in so far as modelling fuel consumption was concerned.

Figure 14.6 illustrates the fuel consumption/speed relationship for the same laden vehicle running with favourable total resistance values from -10 to -2%. At speeds in excess of 10 km/h, fuel is consumed at an approximately constant rate, varying between 7-9ml/s. If the

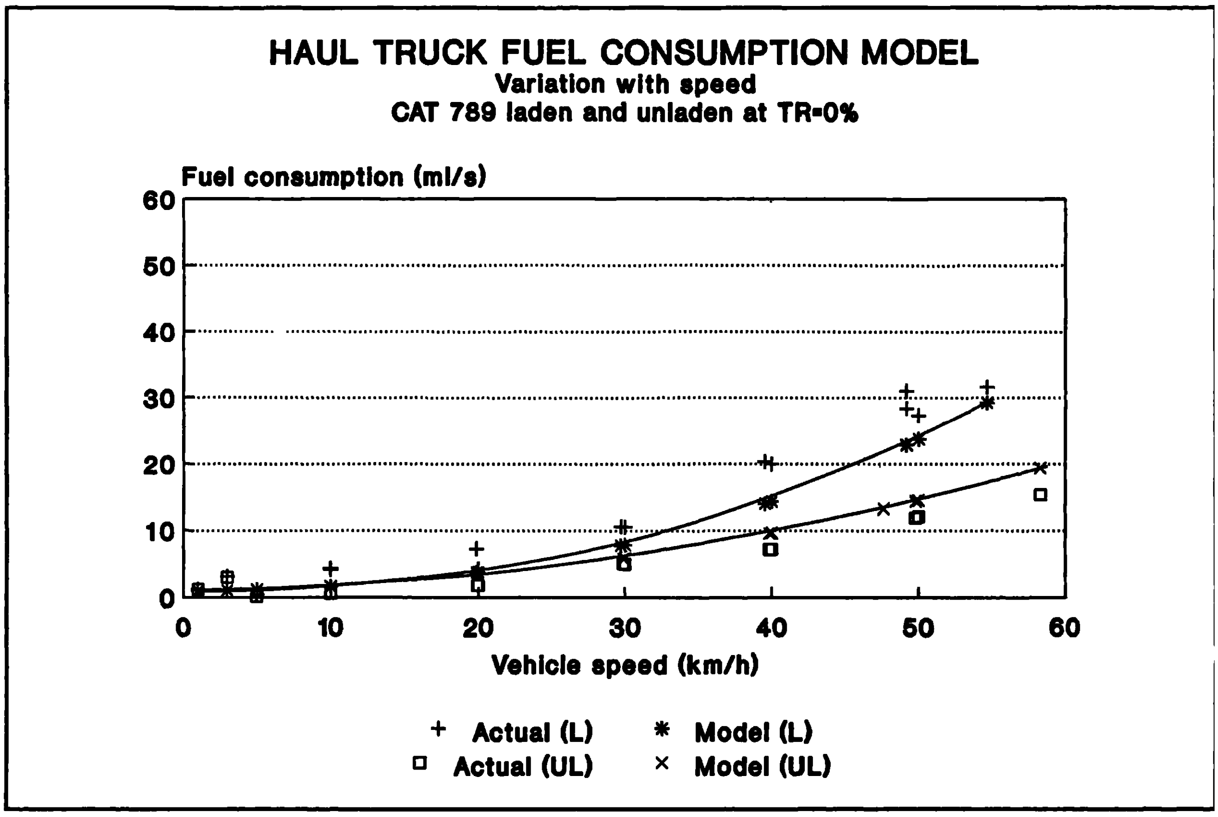


Figure 14.4 Haul truck fuel consumption variation with speed for TR=0%

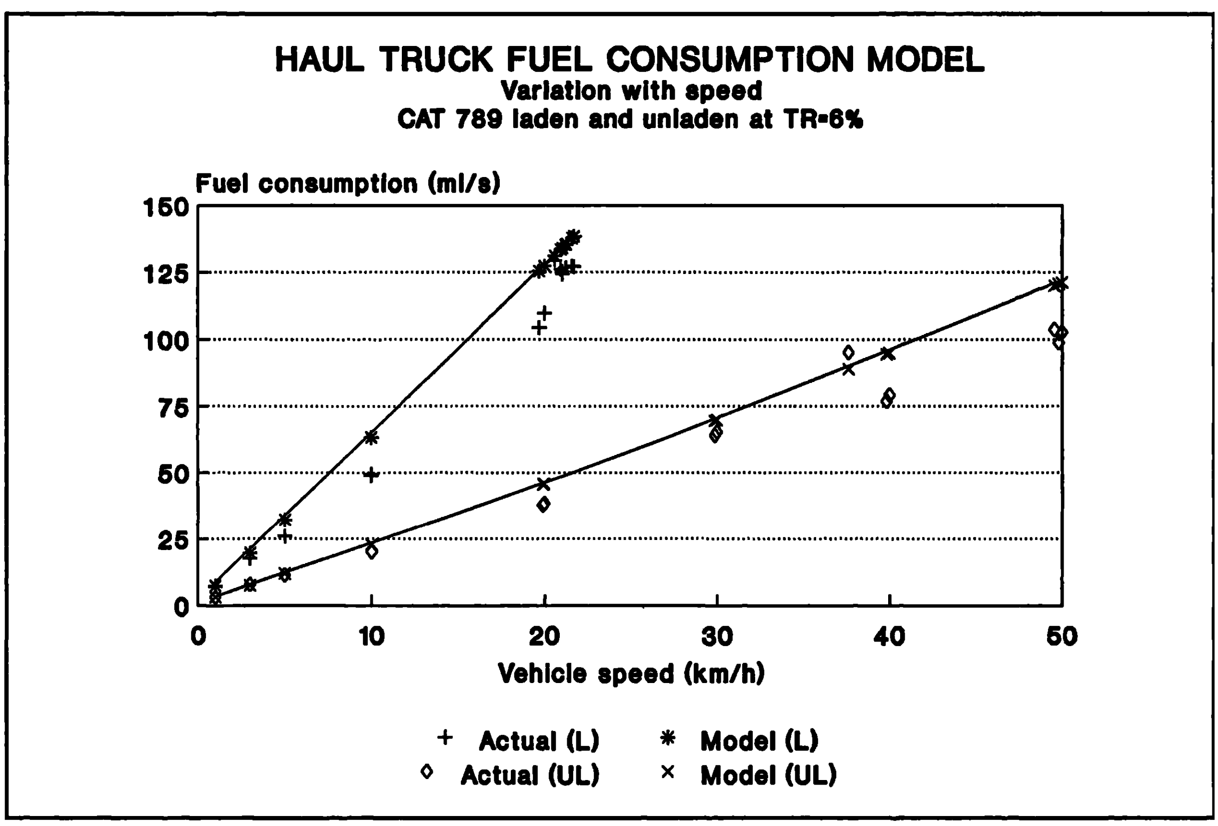


Figure 14.5 Haul truck fuel consumption variation with speed for TR=6%

same data is analysed in terms of consumption variation with total resistance as shown in Figure 14.7, it is seen that consumption remains approximately constant over the range of 0 to -9% (equivalent to 0 to -6% grade if an upper limit of 3% rolling resistance is assumed). From the summary of mine haul road geometric parameters presented in Appendix O it is seen that the majority of roads do not exceed a favourable grade of 2% whilst the much shorter ramp sections do not generally exceed 5%. It is thus feasible to adopt a model in which fuel consumption remains fixed irrespective of the favourable total resistance value. Although this will incur at worst a 20% over-estimation in fuel consumption at total favourable resistance values in excess of 10%, the limited incidence and length of these sections on mine haul roads validates the approximation.

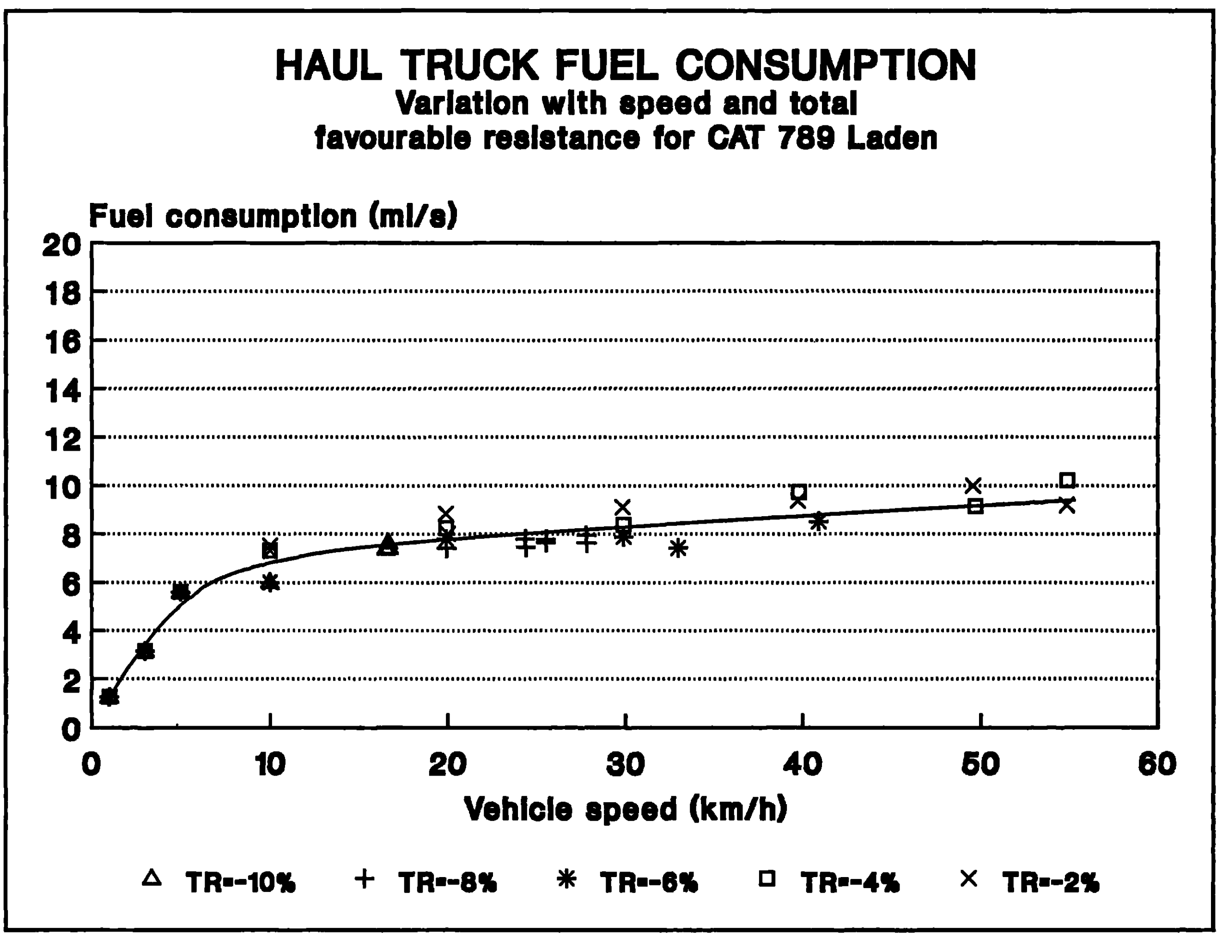


Figure 14.6 Haul truck fuel consumption variation with speed and favourable total resistance.

For sections of haul road in which a favourable total resistance exists (ie. GR+RR<0%), the associated fuel consumption (FCF) and vehicle speed will be limited by the retarder

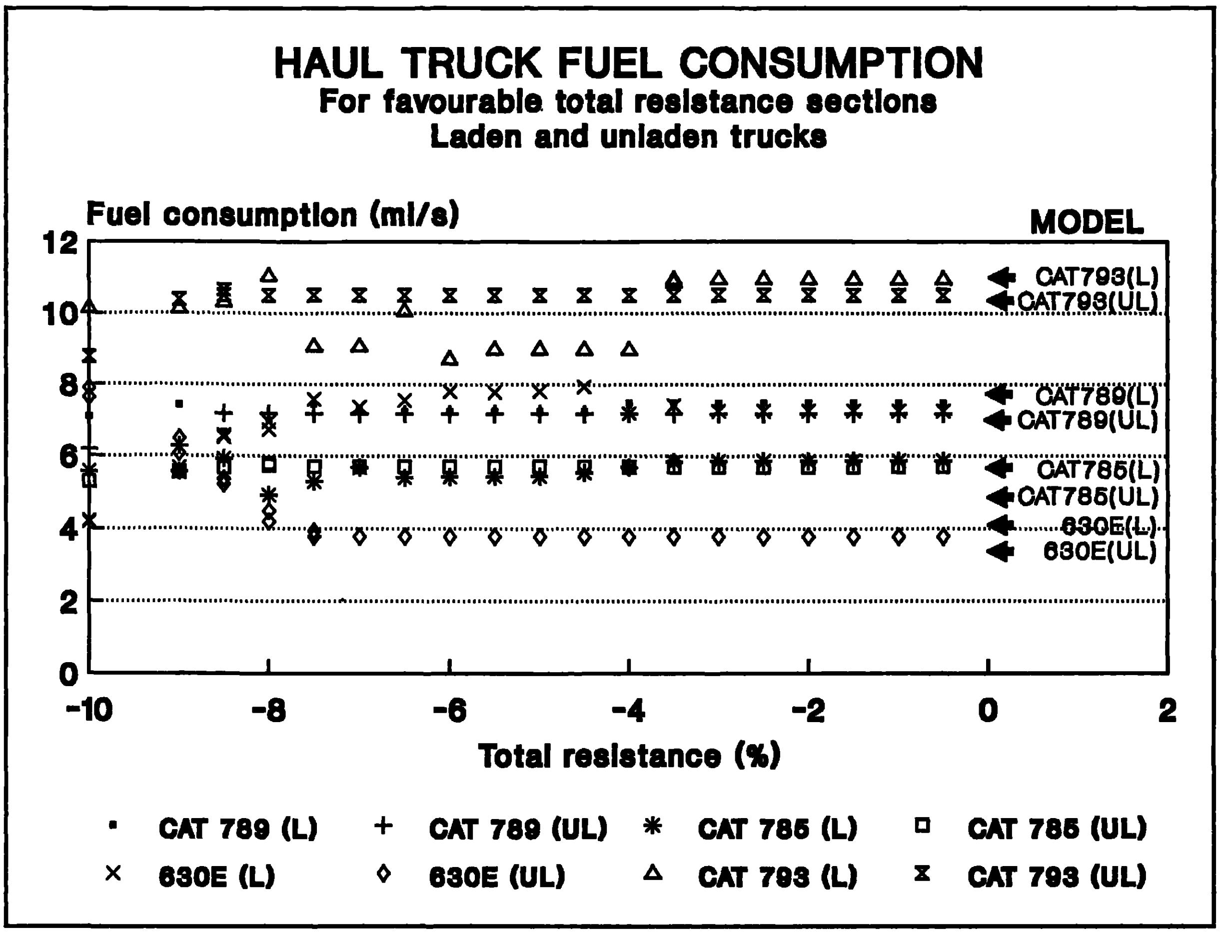


Figure 14.7 Haul truck simulation fleet fuel consumption variation with favourable total resistance.

performance and the effect of total resistance is largely obscured, whilst for sections of road where unfavourable total resistance exists, fuel consumption (FCU) increases with resistance and speed. Thus two models for fuel consumption are required to fully evaluate a particular haul.

The model derived for fuel consumption where total resistance is unfavourable is given below in Equation 14.9.

$$FCU = 1{,}02 + (UVM.V(296.TRU + 4{,}5.V) + L.GVM.V(246.TRU + 0{,}027.V^2)).10^{-5} \qquad 14.9$$

Where

FCU	=	Fuel consumption (ml/s) for unfavourable total resistance
GVM	=	Gross Vehicle Mass (t)

UVM	=	Unladen Vehicle Mass (t)
V	=	Speed of truck ($VUFL$ or $VUFUL$) (km/h)
TRU	=	Total resistance (unfavourable, $\geq 0\%$)
L	=	Truck loading
		1 for laden trucks
		0 for unladen trucks

The model has an R-squared value of 64%, a standard error of 39,2 and an F value of 295 which is significant at better than the 0,001% level for a sample size of 665. Full statistics are given in Table 14.2 from which it is seen that the both the intercept and vehicle mass/speed coefficients do not figure significantly in the model but are a requirement to simulate idling fuel consumption (at V=0) and fuel consumption when TRU=0. Typical model results are illustrated in Figures 14.4 and 14.5 for the Caterpillar 789 truck.

The model developed for fuel consumption on favourable total resistance sections is given in Equation 14.10.

$$FCF = -3{,}575 + UVM(0{,}092 - 0{,}016.DV) + 0{,}0017L.GVM \qquad (14.10)$$

Where

FCF	=	Fuel consumption (ml/s) for favourable total resistance
DV	=	Drive type;
		1 for electric drive
		0 for mechanical drive

The model has an R-squared value of 81% and an F value of 394 which is significant at better than the 0,001% level for a sample size of 271. Full statistics are given in Table 14.2. The drive type indicator is included to accommodate the lower fuel consumption associated with unladen electric drive trucks. Fuel consumption model data points derived according to this model are shown superimposed on Figure 14.7.

Table 14.2 Statistics of Fuel Consumption Models.

STATISTICS OF MODEL ESTIMATION FOR FCU AND FCF								
	STATISTICS OF INDEPENDENT VARIABLES				RANGE OF VALUES			
MODEL	VARIABLE	STANDARD ERROR	t-VALUE	SIGNIF LEVEL OF t-VALUE	MEAN	STD. DEV	MIN	MAX
1 FCU	Intercept	2,32469	-0,82	0,4	-	-	-	-
	UVM.TRU.V	0,00017	16,54	0	9750	10532	0	44386
	L.GVM.V.TRU	0,00012	20,45	0	9207	14132	0	46553
	L.GVM.V^3	2,88E-7	0,94	0,34	2,16E6	6,8E6	0	5,5E7
	UVM.V^2	22,0E-6	2,02	0,04	70445	96550	95	457733
2 FCF	Intercept	0,38307	-9,33	0	-	-	-	-
	DR.UVM	0,00127	-12,59	0	28,3	49,3	0	114
	L.GVM	0,0004	4,18	0	-	-	-	-
	UVM	0,00324	28,4	0	-	-	-	-
INFERENCE SPACE LIMITS FOR INDEPENDENT VARIABLES USED IN MODEL (1) AND (2)								
TRU					5,13	3,46	0	10
UVM					118,7	19,36	95	144
V					23,29	17,15	2,0	58,47
GVM					281,96	54,92	213	362

14.2.4 Verification of Models

The models developed in the previous sections were combined to determine the fuel consumption over a particular mine haul road and then compared to actual fuel consumption from mine records. Limited data is available specifiying total fleet fuel costs or fuel consumption per operating hour which has to be split according to vehicle type and factorised according to operation efficiency (loader and tip delays, queing, etc.) which precludes meaningful comparison with such data. In the absence of operational data, a validation was carried out against the original simulation program, using data from Kromdraai Colliery with which to compare the results. Using the Kromdraai data, the typical fuel consumption of a laden and unladen truck over the route and back is determined. The model derived fuel consumption was based on the same route geometric parameters given in Appendix O and a section average rolling resistance value derived from the models presented in Chapter 13 in conjunction with wearing course material property data presented in Table 3.10. Two rolling resistance values were adopted representing maintenance intervals of 1 and 7 days.

Table 14.3 summarises the results of the validation exercise from which it is seen that the model derived fuel consumption is in broad agreement with the simulation consumptions. An indication of haul truck speeds are also given which, although no comparative mine data is available, appear realistic and compare well with simulation data. The model illustrates the typical increases in travel time and fuel consumption associated with small (2-3%) increases in rolling resistance associated with the particular haul road geometries, wearing course materials, haul truck and traffic volumes modelled. Fuel costs are seen to increase from R12,83/km to R13,13/km for the Kromdraai model, given a fuel price of R1,68 per litre. Although the model appears to overestimate fuel costs by 22% (using an average cost calculated from the 1- and 7-day models), this discrepancy can, in part, be ascribed to the equivocal assumptions necessary in determining the actual mine fuel cost figure.

14.3 Tyre Cost Model

Numerous tyre cost models exist from studies conducted in Brazil, India, the Caribbean and Kenya, as summarised by Chesher and Harrison (1987). Whilst these relate in part to heavy trucks, these are more typical of vehicles operated on public roads and as such are limited to a GVM of 11-50t and tyre sizes up to 1100x22. Tyre costs are related to tyre wear which involves both abrasive wear of the tyre tread and weakening of the tyre carcass. The option of retreading is not pursued in the case of large mine haul trucks due to the high operating temperature and stresses generated within the tyre. In general terms the cost of tyre wear can be stated as;

$$CTW = \frac{CN}{DISTOT} \qquad (14.11)$$

Table 14.3 Results of Model Verification Exercise

Haul road section	1-day model				7-day model			
	Speed (km/h)		Fuel consumption per section (l)		Speed (km/h)		Fuel consumption per section (l)	
	Model	Simulation	Model	Simulation	Model	Simulation	Model	Simulation
KROMDRAAI HR1	27,8	32	43,0	39,0	27,4	31	43,7	40,2
Main (L)	46,8	46	4,4	6,8	46,1	46	4,8	7,5
Ramp-Tip (L)	10,9	8	5,8	3,8	10,8	8	6,0	3,8
Ramp-tip (UL)	20(1)	19	0,2	0,4	20(1)	19	0,2	0,4
Main (UL)	49,5	47	5,6	6,4	49,1	47	5,7	6,2
HR1 (UL)	55,4	53	9,1	15,2	55,3	53	9,3	15,3
TOTAL			**68,1**	**71,6**			**69,7**	**73,4**
FUEL COST (R/km)			**12,83**	**13,49**			**13,13**	**13,83**

NOTES
(1) Assumed speed limit on descent of ramp
L Laden truck
UL Unladen truck
Fuel Price = R1,68/litre

where

CTW	=	Cost of tyre wear (R/km)
CN	=	Cost of new tyre (R)
DISTOT	=	Total distance travelled (km)

In the analysis of tyre costs for large haul trucks a number of problems exist relating to the quality of available data. Since only four mine sites were available, any model of cost variation with road roughness or other geometric parameters will not be particularly robust. In the determination of average haul road roughness over the assessment period a two-fold approach was adopted in which the validity of using IRI roughness values from a single assessment of each road section (as described in Chapter 13.3) was tested against the range of IRI roughness values established from the road roughness progression models presented in Chapter 13.5 and the range of maintenance intervals recorded in Chapter 9 and Appendix F. Table 14.4 summarises the results of the assessment from which it seen that the IRI measurements derived from the single assessment generally fall within the range of expected values. It thus appears reasonable to use these values to generate an average IRI roughness for each mine haul road network, weighted according to individual section length and traffic over the analysis period.

The range of roughness defect scores encountered over the period of assessment for each mine site, as is reflected in Table 14.4, is not large. Whilst individual road sections do exhibit large individual ranges, it is not possible to ascribe a particular truck a specific route, hence the effects of roughness tend to be averaged out.

Other limitations exist with regard to damage attributable to loading or dumping areas as opposed to the road itself, Ingle (1991) reporting that up to 70% of tyre damage may occur in loading or dumping areas. This would obscure any road roughness effect on tyre costs. Limited information from Kriel Colliery on tyre consumption highlights this problem, revealing that 60% of the tyres consumed during the assessment period failed due to puncture, ply separation or side-wall damage. Of those tyres which were scrapped as a result of tread wear only, the tyre life varied between 4700 and 5200 hours, equivalent to approximately 37 600 and 41 600km. Other factors which preclude reliable analysis include

Table 14.4 Comparative Assessment of Mine Haul Road Section and Overall IRI

Mine haul road section	Modelled IRI[1] for minimum and maximum maintenance interval (m/km)			Measured IRI[2] (m/km)	Weighted IRI of mine road network[3] (m/km)
	Min	Max	Average		
KRIEL					5,21
MAIN (Site 3)	4,79	5,29	5,04	4,94	
MAIN (Site 2)	4,78	5,4	5,09	4,81	
RAMP 7				4,87	
RAMP 6	4,59	5,08	4,84	5,92	
RAMP 8/11				6,06	
KROMDRAAI					4,49
MAIN and TIP	4,65	5,37	5,01	4,8	
HR1	4,49	4,86	4,68	3,92	
HR2	4,91	5,24	5,08	4,91	
NEW VAAL					4,30
RAMP-TIP				4,09	
MAIN				4,43	
RAMP 0-2	5,14	6,39	5,77	5,33	
RAMP 2-3				4,89	
RAMP 3-4	4,88	5,63	5,25	5,13	
RAMP 4-6/7				4,63	
RAMP 6/7-9	4,98	5,28	5,13	4,73	
KLEINKOPJE					5,22
MAIN-TIP				7,17	
5W-MAIN	4,63	5,05	4,84	4,76	
R13/14-MAIN				5,71	
2A9-MAIN				4,24	
2A8-MAIN	4,58	5,0	4,79	4,76	
2A7-MAIN				4,81	
3A-TIP				4,96	

Notes

1. Following models presented in Chapter 13.5 and maintenance interval data in Appendix F.
2. Following data in Appendix K corresponding to the test sections modelled in (1) above.
3. Weighted according to section length and traffic volume (ramp sections included but not tabulated)

matching changeouts of tyres to provide a vehicle with a set of tyres of a similar condition, usually involving movement of these tyres between front and rear axles of different machines.

Similar data limitations are seen when haul route geometric parameters are considered. Both the Brazilian and Indian models for tyre costs included expressions for rise and fall and road curvature. Whilst averaging techniques could be applied to generate a typical haul truck route, it would be difficult to deduce any significant model effects for curvature due to the similar and limited geometry of the road studied.

In any MMS model it is the rate of increase of a particular cost item with increasing road roughness which is of major concern as opposed to a fixed cost, although the latter is important in assessing the relative contribution of that cost to total costs. Table 14.5 presents a summary of available tyre consumption data on the basis of cost per kilometre and consumption per 1000km. The cost per kilometre was calculated both from annual costs reported by the mine and from tyre unit costs and consumption data. For a 6-wheel rear dump truck using 3600R51 tyres, costs are seen to vary from R5,14 to R7,98/km and consumption from 0,11 to 0,12 tyres/1000km.

In the absence of suitable data, recourse is made to established models to provide a point of departure in estimating the influence of roughness and geometric parameters on tyre costs. Further research is necessary to assess the validity and transferability of the basic model presented here since only the underlying hypotheses of a roughness- and geometric-related tyre cost relationship can be intuitively deduced, the established model parameter ranges, vehicle types, GVM and tyre types bearing no resemblance to mine haul trucks.

The consumption data presented in Table 14.5 is plotted in Figure 14.8 which shows the tyre consumption/surface roughness relationships developed for commercial trucks from the Caribbean, Brazilian (medium truck only), Indian and Kenyan studies. Consumption at low IRI values appears comparable, despite significant vehicle differences. The model adopted for tyre consumption is expressed in Equation 14.12;

Table 14.5 Summary of Tyre Cost and Consumption Data

TYRE COST AND CONSUMPTION DATA SUMMARY Based on 150-160t capacity rear-dump truck, 6 tyres per vehicle						
	Kriel Mine		Kromdraai Mine		Kleinkopje Mine	
	Vehicle		Vehicle		Vehicle	
Tyre consumption (tyres/1000km)	R170 BD180[3]	0,113 0,462	630EH	0,121	CH130[4]	0,075
Tyre cost (R/km)[1]	R170 BD180	6,77 11,69	630EH	5,14	CH130	4,04
Tyre cost (R/km)[2]	R170 BD180	7,45 13,86	630EH	7,98	CH130	3,37

Notes

1. Calculated from annual tyre costs
2. Calculated from consumption and tyre unit costs
3. Consumption and costs based on 10 3000R51 tyres per 180t capacity bottom dump truck
4. Consumption and costs based on 10 2700R49 tyres per 130t capacity bottom dump truck

$$TW = 0{,}06 + 0{,}012.IRI + 0{,}002\,|GR| \qquad (14.12)$$

where

TW = Tyre wear (tyres consumed per 1000km)

IRI = Road roughness (m/km)

GR = Positive value of road grade (%)

The model predicts a 29% increase in tyre consumption for a 60% increase in road roughness from IRI=5m/km. This equates to an increase in cost of R2,38/km from a cost of R5,18/km at IRI=5, assuming a new tyre cost of R66 000. The effect of road geometry on tyre consumption is modelled as an increase in consumption with grade of road, a 1% change in grade resulting in a 1,6% increase in tyre consumption at IRI=5. No curvature effects were modelled since this effect is generally assumed to be insignificant for large trucks (Chesher and Harrison, 1987).

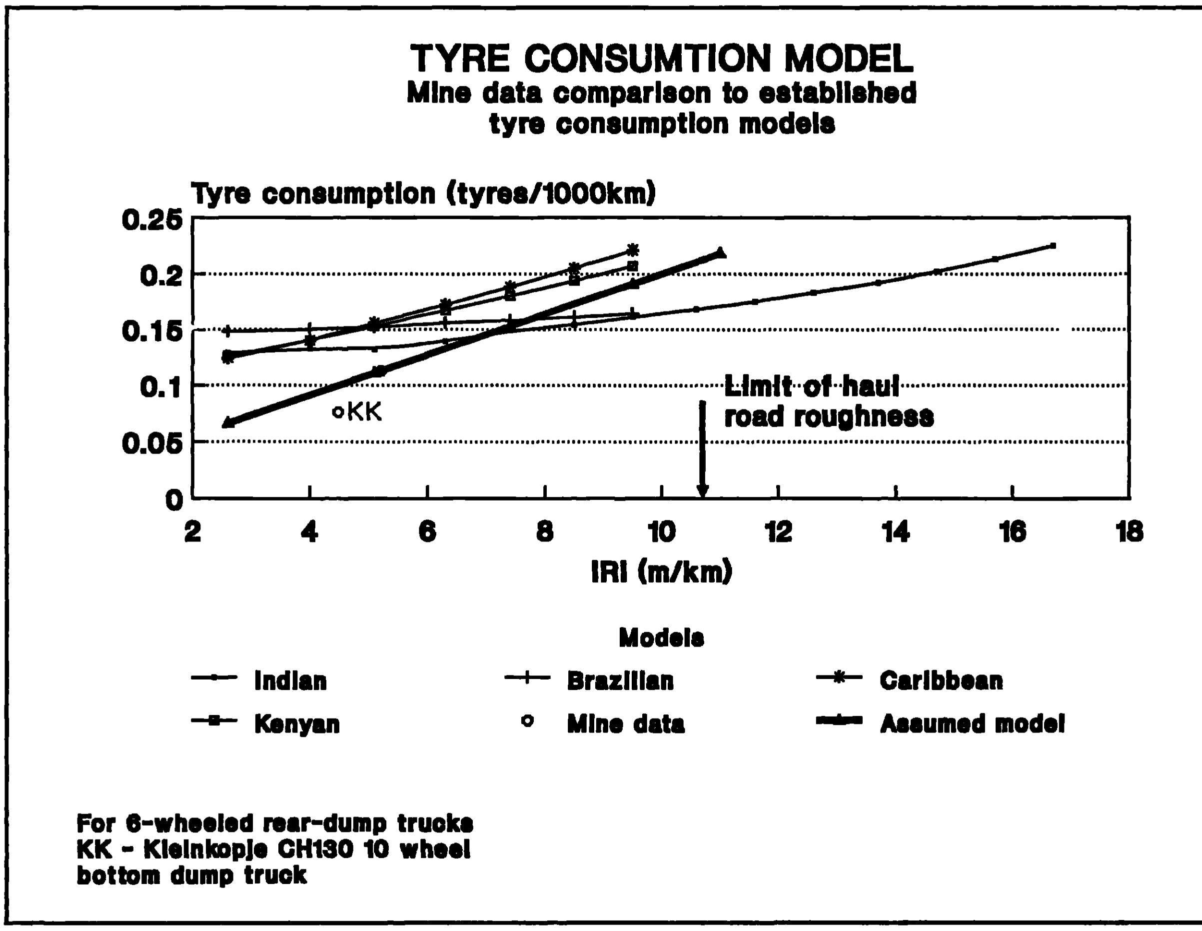


Figure 14.8 Assumed haul truck tyre consumption model in comparison to established models

14.4 Vehicle Maintenance Cost Models

Vehicle maintenance and repair costs comprise both the cost of the parts consumed and the labour hours expended on the repair and maintenance of the vehicle. These costs are related to the type of vehicle, its age, how the vehicle is used and route characteristics. This cost component of the total vehicle operating cost has been shown to be a significant contributor to the benefits from road improvements; up to 80% of the benefits in certain public road projects (International Study of Highway Development and Management Tools, 1995). For the case of haul trucks operating on mine roads similar effects can be hypothesised with reference to the stress sensitivity of large haul trucks as reported variously by Kondo (1984), Deslandes & Marshall (1986) and Taylor & Hurry (1987).

Similar data limitations exist with respect to individual mine parts and labour cost data as explained in Chapter 14.3 with additional complications of costs not being easily ascribed to a particular vehicle type where more than one vehicle type is used for coal hauling and the influence of high cost long-life replacement parts fitted during the period of assessment. The available data does not permit a reliable breakdown of costs on a per vehicle basis and parts consumption history is insufficient to derive suitable weighting coefficients for high cost long-life parts. The analysis, interpretation and transferability of any data generated will be dependant on individual mine maintenance strategies, speeds, loads, driver behaviour, the level of preventative maintenance and the history of the vehicle. It may be anticipated that across mine differences exist in policy and expenditure on maintenance which should ideally be addressed statistically when comparing results.

With these data limitations in mind, recourse was made to established models to provide a suitable point of departure in estimating suitable models for parts and labour costs. Limited data is available with which to corroborate such models but further research is necessary to verify the validity and transferability of the models proposed.

The general form for established models for parts and labour costs are given below in Equation 14.13;

$$\begin{aligned} \text{Parts cost} &= f(\mathit{IRI},\ \mathit{vehicle\ age}) \\ \text{Labour cost} &= f(\mathit{parts\ cost},\ \mathit{IRI}) \end{aligned} \qquad (14.13)$$

where

Vehicle age	=	Total vehicle operating hours (h)
IRI	=	Road roughness (m/km)

The absence of geometric effects is partially explained by Chesher and Harrison (1987) with reference to the aforementioned user-cost studies for commercial heavy vehicles in which speed and load reduction effects were postulated as being the main reason why geometric effects were negligible and poorly determined in these models. In the case of mine haul trucks, load reduction effects are not applicable and the vehicle speed is generally a function of maximum vehicle power and retarder performance as opposed to any driver-applied limit. The majority of haul road networks incorporate unfavourable grade resistance on the laden-haul and, coupled with the greater exploitation of engine capacity on any section of haul irrespective of grade, these effects can be discounted. In addition, with reference to Appendix O it may be seen that the weighted (laden) haul grades are approximately similar for each mine, ranging form 1,1% to 1,91%. With regard to curvature, no effects are predicted for the same reasons as mentioned in Chapter 14.3.

14.4.1 Vehicle Parts Cost

The common practice of road user cost studies has been to express the parts consumption in terms of a standard parts cost. This represents the parts consumption as a fraction of the replacement price of the vehicle as given in Equation 14.14.

$$\text{Standardised parts cost} = \frac{P}{VP} \qquad (14.14)$$

where

P = Parts cost (R/1000km)

VP = Replacement price of vehicle ($Rx10^5$)

The general form of the models presented in the user-cost studies previously discussed incorporate a roughness and multiplicative age effect. A linear increase in standard parts cost for increasing roughness is predicted whilst the contribution of vehicle age to parts cost is predicted at a progressively reducing rate with age. The contribution of grade effects is assumed linear.

The available data from each mine was analysed on a fleet, as opposed to a vehicle basis and whilst the resultant model can be seen as applicable to both rear-and bottom-dump trucks, the limitations of this approach (especially with regard to the different vehicle designs and variations in vehicle drive systems) should be borne in mind. Table 14.6 summarises the available standardised cost parts data from each mine.

Table 14.6 Standardised Haul Truck Parts Costs

	Kriel Colliery	Kriel Colliery(1)	Kromdraai Colliery	New Vaal Colliery	Kleinkopje Colliery
Fleet	R170 (5)(E) BD180 (3)(TT)	R170 (5)(E)	HD630EH (7)(E)	R170 (6)(E) HD1600M (5)	CH120 (4)(TT) CH130 (5)(TT)
Annual fleet t.km (single trip)	33 496 000	33 496 000	19 266 100	46 376 350	25 481 000
Annual fleet km	408 487	158 160	236 393	301 145	407 696
Annual fleet parts cost (R)	1 106 890	66 134	996 373	7 962 554(1)	811 340
Average replacement vehicle cost (Rm)	1,7	1,7	1,83	1,9	2,4
Standardised parts cost	159	247	230	-	80
Average fleet age (hrs)	11 072	11 865	8 745	14 400	4 898

Notes
1. Based on estimated parts cost for R170 fleet alone
TT Truck-trailer combination, bottom dumper, mechanical drive
E Electric drive
(1) Tyre, parts and labour costs not specified separately

Considerable variation in the standardised parts cost is evident and when assessed in relation to average road roughness as given in Table 14.4, no trend is apparent over the small range of roughness representing each mine haul road. However, using this data as a rough guide, the model illustrated in Figure 14.9 and 14.10 was derived from the form of the established models described previously. The parts cost model is expressed as;

$$\frac{P}{VP} = (4+20.IRI).H^{0,375} \tag{14.15}$$

where

H = Vehicle age (total operating hours) ('1000hrs)

The model predicts a 57% increase in standardised parts cost for a 60% increase in road roughness from IRI=5, given a vehicle age of 5000 hours. If vehicle age is doubled, the standardised parts cost is seen to increase by 29% given a road roughness of IRI=5m/km. In terms of parts cost/km, these roughness and age increase effects represents a cost increase of R1/km from R3,23/km for a truck costing R1,7m. This compares to mine cost data which varies between R2,09 and R4,03/km.

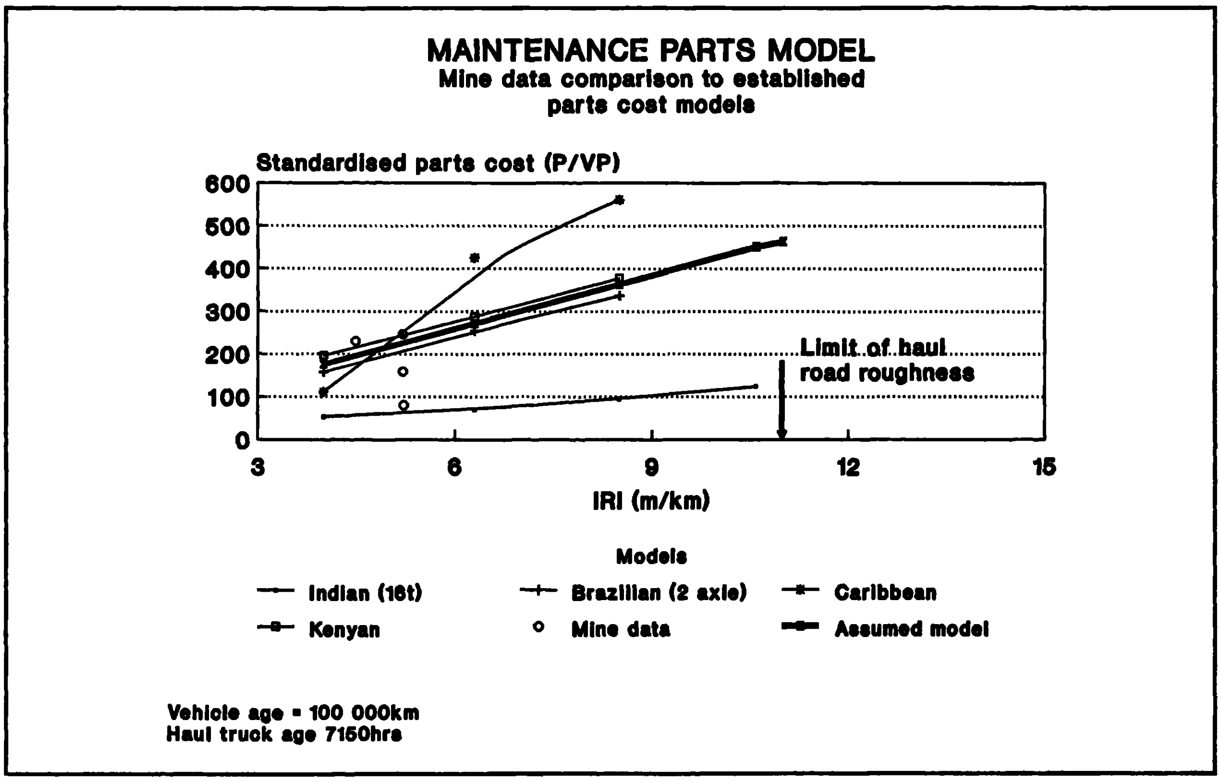


Figure 14.9 Proposed parts cost model for mine haul trucks showing effect of increasing road roughness

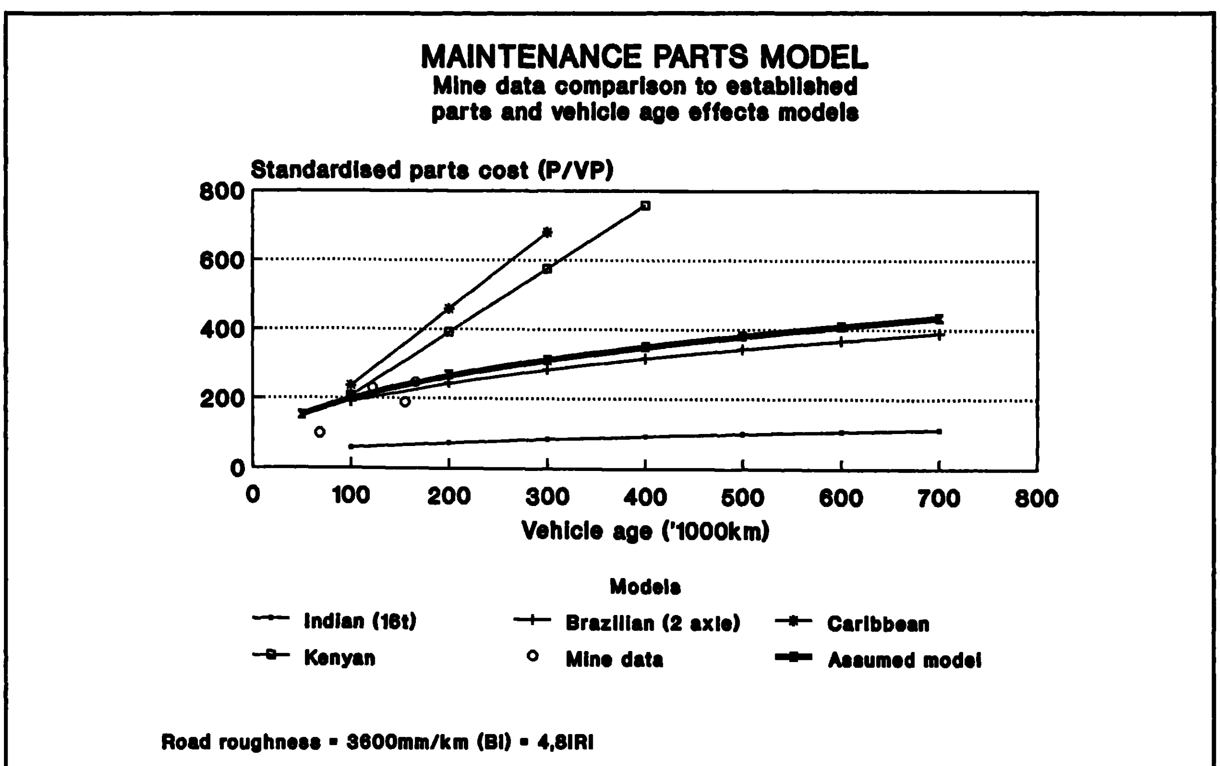


Figure 14.10 Haul truck age effects on parts cost

14.4.2 Vehicle Labour Costs

The approach advocated in the estimation of labour cost involves relating maintenance labour quantity per unit distance to parts consumption per unit distance and highway characteristics as discussed by Chesher and Harrison (1987) with reference to the Brazilian, Indian and Kenyan road-user cost studies. The Caribbean study reports in terms of labour costs and wage rates are not provided with which to compare this data to the other studies. Maintenance labour again proved to be a difficult item on which to obtain usable information as most mines carried out a combination of in-house and contractor repairs and no hourly record was kept of the former in the case of individual vehicles or vehicle types in a mixed fleet. Whilst the absence of an hourly labour rate limits the extent to which established models can be used directly (on a cost basis), a basic model can nevertheless be derived based on the hypothesised interaction of the dependant variables of standardised parts cost and road roughness as given in Equation 14.13.

The form of the models adopted in the Indian and Brazilian studies is given below in Equation 14.16.

$$L = a\left[\frac{P}{VP}\right]^{b} \qquad (14.16)$$

where

L	=	Labour hours or cost per 1000km
a,b	=	Coefficients

The coefficient *b* is reported to be less than unity, varying from 0,47 to 0,65 for buses and trucks. Increases in parts costs are predicted to lead to an increase in labour costs but at a decreasing rate which may reflect the relatively capital intensive nature of major repairs on large haul trucks and their unitised construction. Engines, wheel motors, etc. are often removed as a complete unit to be repaired off-site by contractors, the only labour cost being recorded arising as a result of removal and replacement of items as opposed to their repair. The coefficient *a* is found to be affected by road roughness in some studies, both increasing the labour cost (with fixed parts cost), suggesting that maintenance activities for vehicles on rough roads are relatively more labour intensive, and decreasing the labour cost implying less labour at a given parts cost being applicable for rough roads. In each case only small and poorly determined effects were reported for commercial trucks. In the case of mine haul trucks, due to their unitised construction it may be anticipated that no additional road roughness effect will be present, other than that included in the standardised parts cost appearing as an explanatory variable.

In estimating the form of a model describing haul truck vehicle maintenance costs, limited data from the participating mines provides a starting point. Plotting labour cost (R/1000km) against standardised parts cost, as shown in Figure 14.11 reveals an approximate trend which is described in Equation 14.17.

$$L = 220\left[\frac{P}{VP}\right]^{0,45} \tag{14.17}$$

where

L = Labour cost (R/1000km)

The model approximates the increasingly capital intensive nature of major repairs, albeit at a lower rate of increase than for the Brazilian and Indian models which are illustrated in Figure 14.11, an assumed hourly labour cost being applied only for comparison purposes. To ensure transferability of the model, a labour cost-increase factor should be applied based on the 1994-1995 average hourly labour rate incorporated in these figures.

14.5 Road Maintenance Cost Model

The road maintenance activities of blading and watering were introduced in Chapter 2 as they apply to mine haul roads. Since total costs incorporate both vehicle operating and road maintenance costs elements, as seen in Figure 2.2, it is evident that the minimisation of total costs must incorporate an estimate of road maintenance cost per kilometer. The road maintenance operating cost per kilometer comprises both grader and water car operating costs. Although not contributing directly to a reduction in road roughness, the incorporation

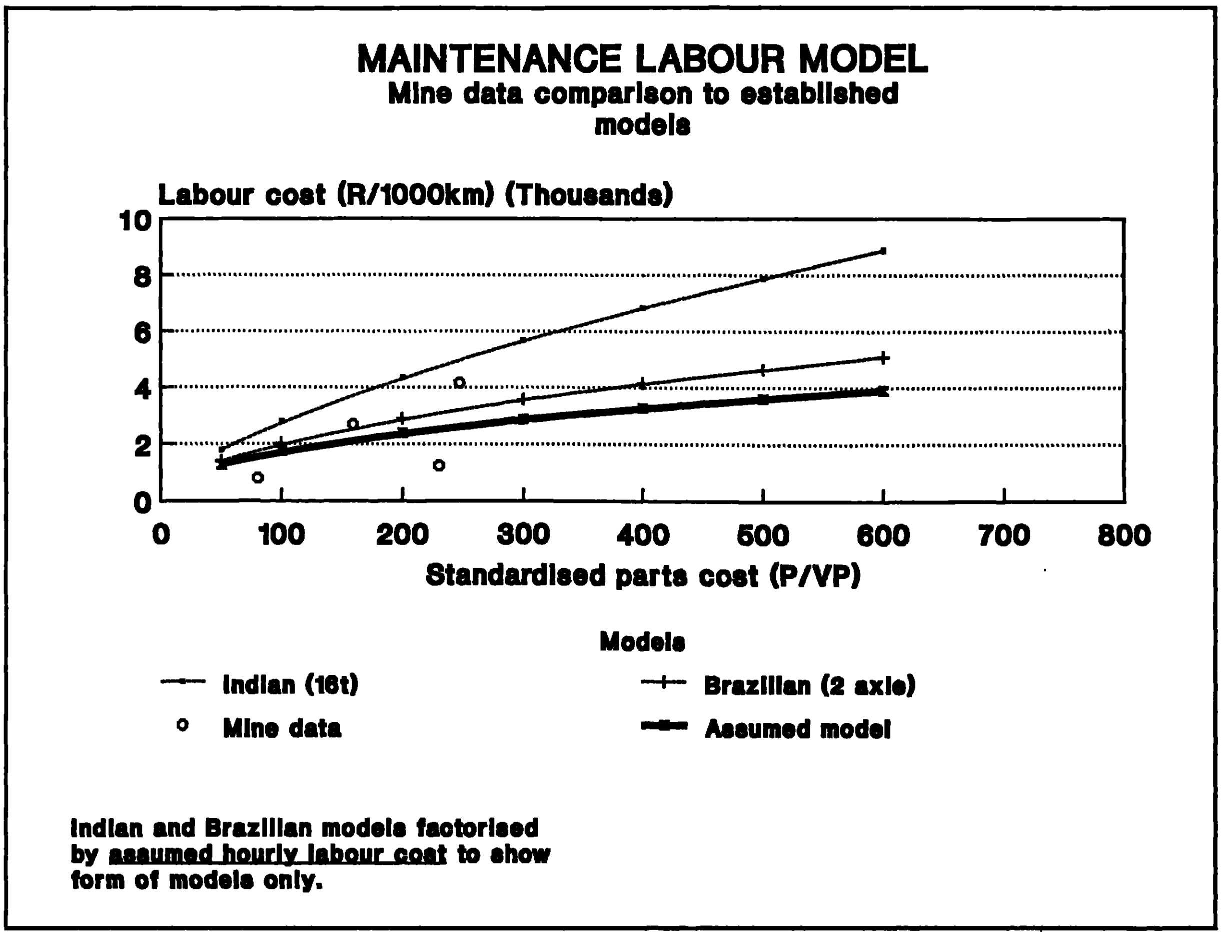


Figure 14.11 Proposed labour cost model variation with standardised parts cost

of the watering costs in the maintenance costs model is intended to reflect (ideal) operating practice in which, immediately after blading, the section of road is watered to reduce dust, erosion and aid recompaction.

Table 14.7 summarises the road maintenance fleet productivities and costs for the 1994/1995 financial year for three participating mines. From observation and discussion with operating personnel at each mine, grader and water-car productivity was theoretically calculated based on a road width of 24m, a blade or spray pass-width of 3 and 12m, maximum vehicle speeds during operation and annual vehicle operating hours. This gave a productivity of 0,75 and 6,25km maintained road per operating hour for each machine respectively. The total number of kilometer-passes per day varied between 23 and 56 depending on the daily operating hours of each grader. Whilst no productivity standards have been published with regard to mine haul road maintenance, a figure of between 8-18km of maintained road per 16 hour day is quoted by mine personnel which is in broad agreement with the theoretically calculated

Table 14.7 Summary of Road Maintenance Costs and Productivities

SUMMARY OF ROAD MAINTENANCE FLEET COSTS AND PRODUCTIVITIES						
	KRIEL		KROMDRAAI		KLEINKOPJE	
	GRADER	WATERCAR	GRADER	WATERCAR	GRADER	WATERCAR
Make	CAT 14G	EUCLID W50	CAT 14G	HD465/325	CAT 14G	HD465
Number in use	2	1	3	2	3	2
Annual operating hours (hrs)	5290	2838	6900	3649	3273	3616
Annual operating cost (R)	351520,50	221874,84	428256,00	434362,00	224102,31	269319,68
Operating cost per hour (R)	66,45	78,18	62,07	119,04	68,47	74,48
Production (ROM ton.km/day) (single trip)	119291	119291	68611	68611	90744	90744
Daily cost (R/t.km)	2,95	1,86	6,24	6,33	2,47	2,97
Daily t.km per machine	59645,50	119291,00	22870,33	34304,35	30248,00	45372,00
Road width (m)	24	24	24	24	24	24
Blade or spray width per pass (m)	3	12	3	12	3	12
Time to complete single pass (min)	10,0	4,8	10,0	4,8	10,0	4,8
Productivity (km/op.h)	0,75	6,25	0,75	6,25	0,75	6.25
Productivity (km passes/day)	56,52	126,34	49,15	81,22	23,31	80,48
Annual kilometers	3968	17738	5175	22806	2455	22600
Operating cost of machine (R/km)	88,60	12,51	82,75	19,05	91,29	11,92
TOTAL ROAD MAINTENANCE COST (R/km)	**101,11**		**101,08**		**103,21**	

productivity of 0,75km/hr.

The assumption of a single blade-pass was adopted in this analysis on the basis of observation. However, with reference to the roughness defect descriptions of degree and extent (Tables 13.1 and 13.2) most operators envisaged an increase in the number of blade-passes required to achieve an acceptable finish when the roughness defect score exceeded degree 3 and extent 3. A productivity curve is thus proposed, incorporating this reduction in grader productivity associated with excessively rough roads as shown in Figure 14.12. A similar approach is adopted by Visser (1981) in which road grader productivity is reduced with increasing road roughness.

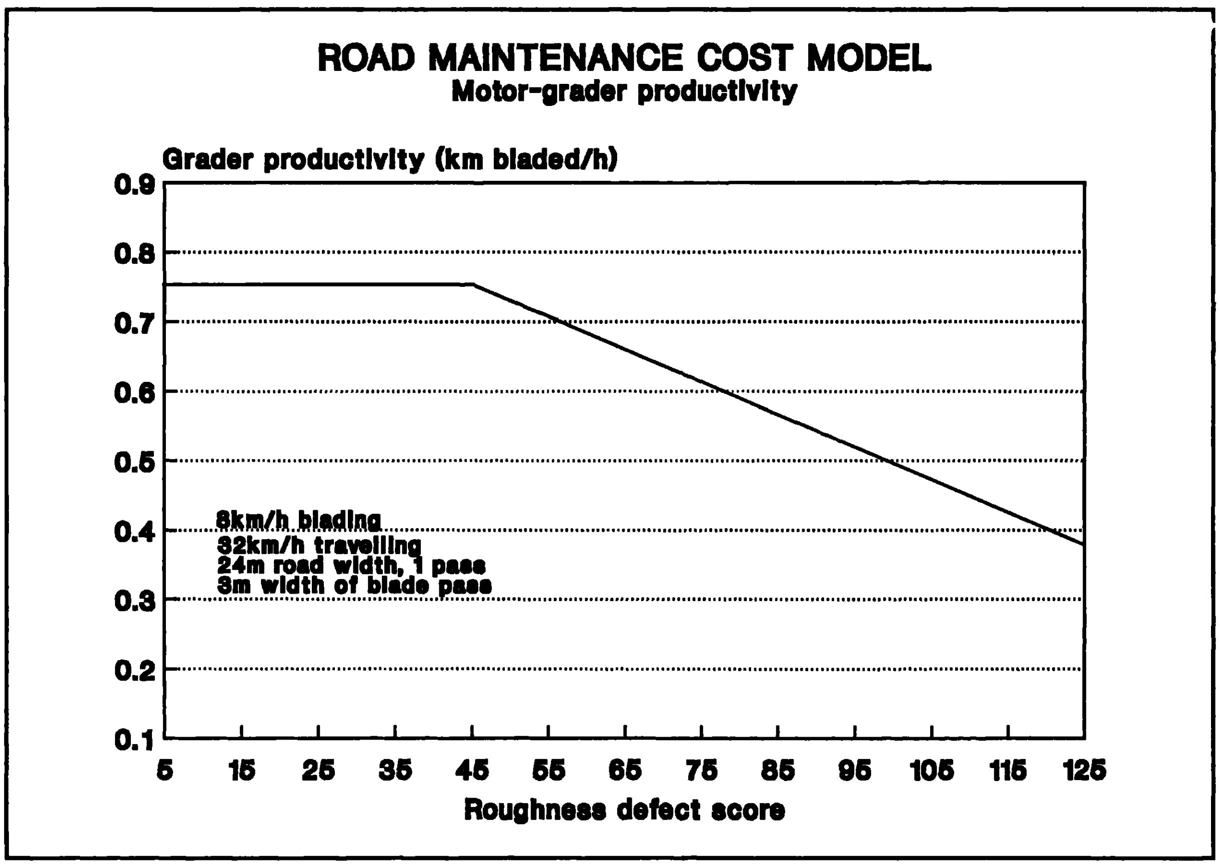


Figure 14.12 Productivity of a motor-grader during routine haul road maintenance operations.

The hourly operating cost for both grader and water car appear similar except for Kromdraai Mine where a smaller (32,5t) water car is used along with a 46,5t, the latter being more typical of the other mines. The fleet size recommendation (Long, 1968) of 1 grader per

45 000 daily ton-kilometer of production cannot be confirmed from this data although it would appear (from a road maintenance point of view) that the Kriel Colliery grader fleet is too small for the daily ton-kilometres produced whilst that of Kromdraai too large. The fleet size recommendations can be more reliably determined from a MMS solution incorporating specific material roughness defect progression models and traffic volumes as described in the following chapter. Nevertheless, the total road maintenance costs appear very similar, ranging from R101,08 to R103,21 per kilometre road maintained. For the purposes of the MMS model, these figures are user-defined, allowing escalation of the maintenance costs if necessary.

The road maintenance cost model is thus constructed from consideration of the average blade width per pass, road width, roughness defect score before blading, motor-grader productivity curve and cost per hour from which the motor-grader cost per kilometre is found. This cost is then combined with the cost per kilometre of the water-car and workshop costs to produce a total cost per kilometre for road maintenance.

14.6 Summary and Conclusions

The development of a mine haul truck vehicle operating cost model comprising the components of fuel, tyre, maintenance parts and maintenance labour was addressed in this chapter, together with a model of road maintenance activities in terms of the cost per kilometre for grader and water car. The combination of the road maintenance and vehicle operating cost models enables the optimal maintenance strategy to be sought based on the minimisation of these costs over a particular haul route.

The fuel consumption model development was based on a haul truck simulation package in which engine torque/fuel consumption maps were used in conjunction with vehicle speed/rimpull and retarder force/speed/distance maps to simulate the operation of a truck over a defined course. A number of rear dump trucks were chosen for simulation, representing typical vehicles operated or likely to be operated by strip coal mines. The similarity in speed versus total resistance performance of these trucks prompted the development of four universal equations by means of which vehicle speed could be predicted for any combination of total resistance and truck loading.

The constant speed fuel consumption model was used as an explanatory variable in the fuel consumption model in which equations were developed for the fuel consumed by trucks on both favourable and unfavourable total resistance segments of a haul route. Fuel consumption was seen to vary with vehicle speed, laden and unladen mass and total resistance for unfavourable resistance sections. For favourable resistance sections, fuel consumption was seen to be approximately constant for a particular truck type between 0 and -9% resistance, the maximum downhill speed of the vehicles being approximately similar and controlled by retarder performance. The fuel consumption model developed thus incorporated only vehicle loading and drive as explanatory variables. The verification of the models to actual mine data proved problematic since no fuel consumption test data was found with which to validate the models. An approximate fuel consumption figure was deduced from mine operating records and vehicle annual ton-kilometres which exhibited broad agreement with the model when applied over a similar haul route. It is recommended however, that on-site fuel consumption tests be conducted with which to rigorously verify the fuel consumption models adopted.

With regard to the tyre, vehicle maintenance parts and maintenance labour models developed, similar data limitations were seen which precluded the development of statistically robust models. The approach advocated involved the analysis of existing models developed for commercial trucks used on public roads. 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. These models were then compared with the limited mine data available to verify the order of magnitude of the costs modelled and to indicate the likely rate of change of these costs with road roughness. The latter proved particularly problematic due to data characteristic limitations and it is recommended that further research be conducted to assess the validity and transferability of the basic models proposed.

CHAPTER 15
A MAINTENANCE MANAGEMENT SYSTEM PROGRAM FOR MINE HAUL ROADS

15.1 Introduction

The interaction and influences of the various models proposed to represent vehicle operating costs (VOC), road maintenance costs and the progression of road roughness as developed in Chapters 13 and 14 can only be effectively analysed using a systems analysis approach. The conceptual outline of a maintenance management systems (MMS) model was discussed in Chapter 3 and illustrated in Figure 3.12 and this is used as a basis for developing an appropriate model for mine haul roads. Details of program input parameters are given prior to a discussion of the computational phase and an analysis of sample output reports. These reports are evaluated in the light of both established maintenance activities on participating mines and the sensitivity of results to variations in key input parameters.

15.2 The MMS Model

The objective of producing a MMS model for a mine haul road network was to evaluate alternative maintenance strategies within a system of constraints related to total cost and maintenance quantities such that the optimal maintenance policy for the network, commensurate with lowest total costs, could be identified. The basis of the evaluation were road user costs, consisting of haul truck fuel, tyre, parts and labour costs together with road maintenance costs for both the road grader and water-car. Road construction and vehicle depreciation costs were not considered since these will be the same irrespective of the maintenance strategy evaluated.

A complete listing of the program is given in Appendix P based on the flow-chart presented in Figure 3.12, repeated for each maintenance strategy evaluated. The program is written in QBasic version 4.5 in a modular self documenting format, readily allowing the modification of the various sub-programs representing each model previously developed. A basic error handler is incorporated to trap common data errors. The program may be split into four operations concerning data input, calculation of the various cost components of total road-user cost, selection of the optimum maintenance strategy and the reporting of the results.

15.2.1 MMS Model Data Input

The input phase of the program is divided into six active input screens, the first being a general introduction to the MMS methodology, specifying program objectives and general data requirements. The following data input screens are given in Tables 15.1 to 15.5 as an aid to clarifying the scope of the MMS program for mine haul roads. The mine haul road network is divided into a number of specific road links corresponding to changes in haul road geometry, wearing course materials or the daily tonnage a particular section carries. The screen shown in Table 15.1 allows the user to specify data relating to the type of haul truck operated common to each segment specified. On completion of data input the option is provided to edit the data if necessary. As discussed in Chapter 14 only rear dump trucks are accommodated in the program. Table 15.2 contains details pertaining to the road maintenance fleet, specifically the number, daily operating hours and hourly operating costs of the road grader and water-car.

The haul road is sub-divided into a number of segments as described previously. Each such link as determined by the user is assigned a segment number and the required segment data, in terms of geometry, tonnage and wearing course material properties is specified as shown in Table 15.3. The input data shown in Table 15.4 is designed to permit unit cost factors to be included in the calculation of costs. An escalation factor for (workshop) labour costs is included since the labour cost model developed in Chapter 14 is based on a per kilometre cost as opposed to labour hours cost thus any escalation in labour rates should be reflected in the labour cost model. Unit prices can also be specified for diesel fuel and haul truck tyres. The VOC component models for tyre, parts and labour can be modified by the user by altering the coefficients of any model. This input is not compulsory and the program would adopt the default values if no changes are made.

Table 15.1 MMS Program Input - Haul Truck Data

```
                    HAUL TRUCK DATA

                    This data is common to all 3  segments specified

      Vehicle GVM (t)                       271
      Vehicle UVM (t)                       111
      Vehicle drive type, 1-elec, 0-mech    1
      Vehicle replacement price (Rm)        1.83
      Average vehicle age ('1000 op hrs)    1.24

                    If data is correct press C else E to edit.
```

Table 15.2 MMS Program Input - Haul Road Maintenance Fleet

```
                    HAUL ROAD MAINTENANCE FLEET DATA SECTION

      Enter number of road graders available               ? 3
      Enter grader operating hours per days                ? 7
      Enter grader total operating cost Rand per hour      ? 66
      Enter number of water-cars available                 ? 2
      Enter water-car operating hours per day              ? 7
      Enter water-car total operating cost Rand per hour   ? 76

                    If data is correct press C else E to edit.
```

Table 15.3 MMS Program Input - Haul Road Segments

```
Please input values at prompt for each segment specified previously

                    SEGMENT               1       2        3
Segment name                            HR1     HR2      HR3
Length of segment (km)                  0.94    3.24     4.53
Width of road (m)                       24      24       26
Grade of road (%) (uphill positive)     -1.7    0.99     0.55
Average segment speed (20-50kph)        40      40       45
Daily tonnage hauled (kt)               15      7.7      7.3

Material properties of section
Material type, 1-mixes, 0-fericrete     0       0        0
California Bearing Ratio (%) CBR        46      50       162
Shrinkage product (SP)                  198     196      82
Grading coefficient (GC)                36.3    21.3     30.1
Dust ratio (DR)                         0.6     0.6      0.4
Plasticity index (PI)                   10      8        4

              If data is correct press C else E to edit.
```

Table 15.4 MMS Program Input - Unit Cost Factors

```
UNIT COST FACTORS

Parts and labour costs are based on 1995 prices
Please specify escalation factor? 1

Fuel cost is based on a current diesel price
Please specify diesel price Rand per litre? 1.68

Tyre cost is based on current tyre price
Please specify tyre price (R)? 65000

If data is correct press C else E to edit.
```

Table 15.5 MMS Program Input - Haul Truck VOC Model Data

```
VEHICLE AND MAINTENANCE FLEET COSTS

Do you want to change any cost estimate equations (Y/N)?

VEHICLE AND MAINTENANCE FLEET COSTS

Haul truck operating cost data

1.  Tyre cost (R/km)       TW =  .06 + .012 IRI+ .002 GR%
2.  Parts cost (R/km)    P/VP =  ( 4 + 20 IRI).H^ .375
3.  Labour cost (R/km)      L =  220 (P/VP)^ .45



Enter model number to modify (1, 2 or 3) or C to continue?
```

However, as discussed in Chapter 14, characteristic data limitations prevent the development of robust statistical models for these cost components and as such an improved model may be substituted by the user.

15.2.2 Calculation of Total Road-User Costs

In the case of mine haul roads, road-user costs encompass both vehicle operating and road maintenance costs since the agency controlling the haul road network is also affected by user operating costs. A number of sub-programs evaluate the various models which combine to form the total costs for each maintenance strategy evaluated. Initially, a roughness defect score is calculated for a range of maintenance strategies from daily grading (ie. maintenance interval=0 days) to a 20 day grading interval using Equations [13.9], [13.10] and [13.11] for each segment of the network. The roughness defect score is then translated by means of Equations [13.3] and [13.4] into an equivalent rolling resistance. Since it was shown in Chapter 13 that rolling resistance was dependant on vehicle speed and vehicle speed itself is a function of rolling resistance, an initial estimate of vehicle speed over the section is requested from the user (Table 15.3). This estimate of segment speed is associated with a maximum error of 4% over a speed range of 20km/h at roughness defect scores above 30. Actual vehicle speed is then calculated according to Equations [14.5], [14.6], [14.7] and [14.8] depending on the particular segment total resistance and loading of the truck. The calculation of fuel consumption then follows from Equations [14.9] and [14.10]. The cost of fuel consumption is then found for the particular segment at a particular maintenance interval from consideration of tonnage hauled and total laden and unladen distances travelled over the segment.

The VOC components are calculated according to the models presented in Equations [14.12], [14.15] and [14.17] for tyre, parts and labour cost respectively. Costs are calculated for each maintenance interval from consideration of traffic volume (tonnage hauled) and total laden and unladen distances travelled over the segment. Total VOCs are then found from the sum of each of the fuel, tyre, parts and labour costs for each segment as illustrated in Figure 15.1.

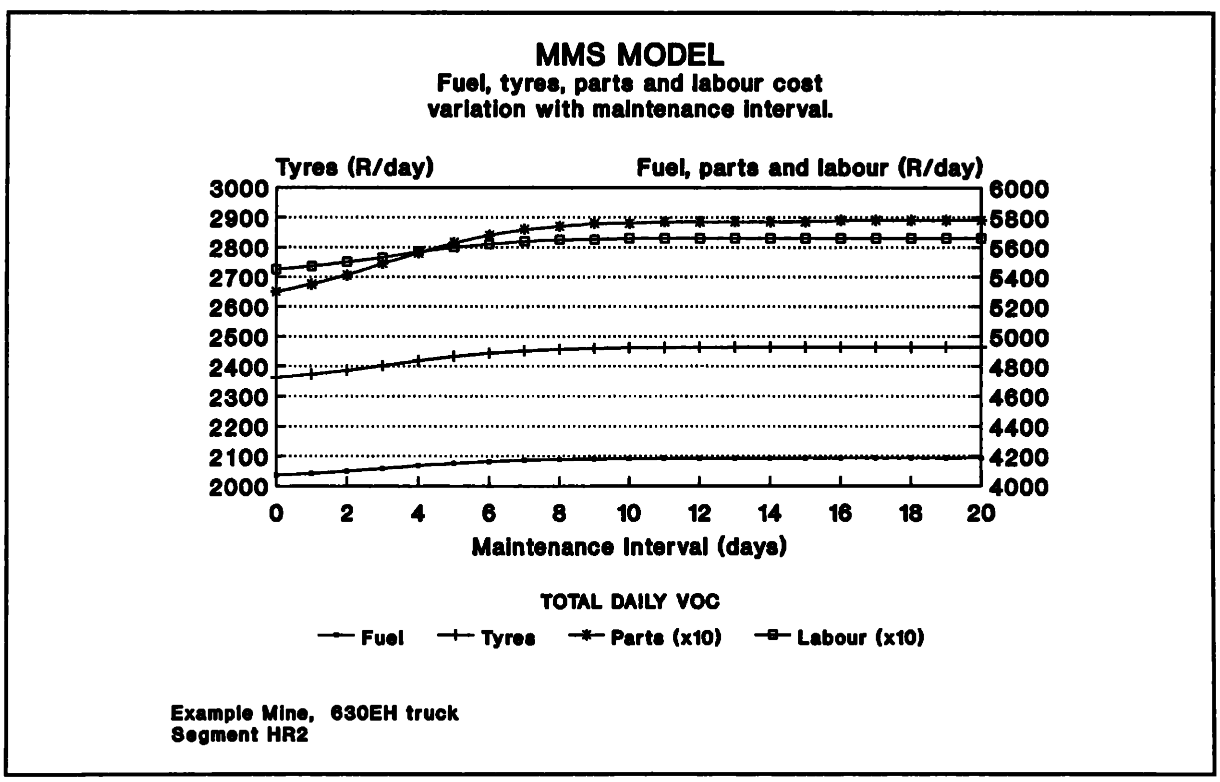


Figure 15.1 Segment VOC Component Variation with Maintenance Interval

The variation in VOC for one particular segment simulation are shown in Figure 15.1. Costs are seen to increase with increasing road roughness arising from the increasing maintenance interval. As predicted by the roughness progression model, the rate of increase reduces with increasing maintenance intervals as the roughness experienced by the vehicle approaches a constant value. The corresponding component costs are summed to give total VOC for each segment under each maintenance interval.

The cost of haul road maintenance is calculated from consideration of the productivity data presented in Chapter 14.5 together with the productivity curve for motor graders presented in Figure 14.12. The daily cost of maintenance is then calculated according to specified hourly operating costs, segment length and width and the roughness defect score relating to the particular maintenance interval. The maintenance cost refers solely to that associated with the particular segment maintenance interval and does not include the cost of additional maintenance activities arising from rain, spillage, spot repairs, etc. Figure 15.2 illustrates the road maintenance cost and total VOC variation with maintenance interval and the resultant total cost profile for one particular segment of network.

15.2.3 Selection of Optimal Maintenance Strategy and Reporting

Each segment comprising the haul road network will have a unique minimum total cost solution dependant on section geometry, traffic volume and wearing course material properties. This is illustrated in Figure 15.3 for a particular network from which it is seen that segment HR1 costs are minimum for a daily maintenance regime, segment HR2 minimum for an interval of two days between maintenance and segment HR3 for an interval of 1 day. Whilst these may represent the optimum maintenance strategy from a minimum total cost point of view, no maintenance equipment fleet productivity constraints have been considered. When maintenance fleet equipment numbers and operating hours are considered, the cost-based optimal strategy may not be attainable with the specified maintenance fleet.

The optimal cost based solution is assessed in terms of required operating hours per day which is dependant on the associated optimal maintenance interval. If available water-car

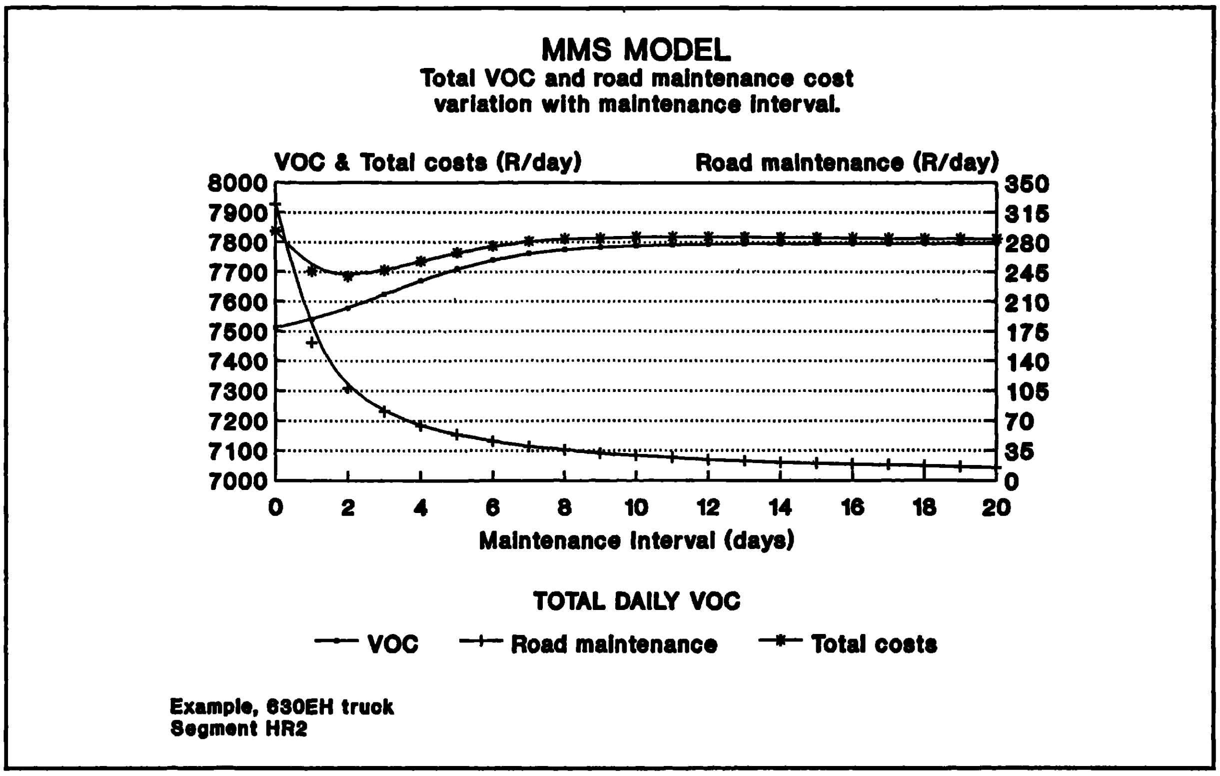


Figure 15.2 Total VOC and Road Maintenance Segment Cost Variation with Maintenance Interval

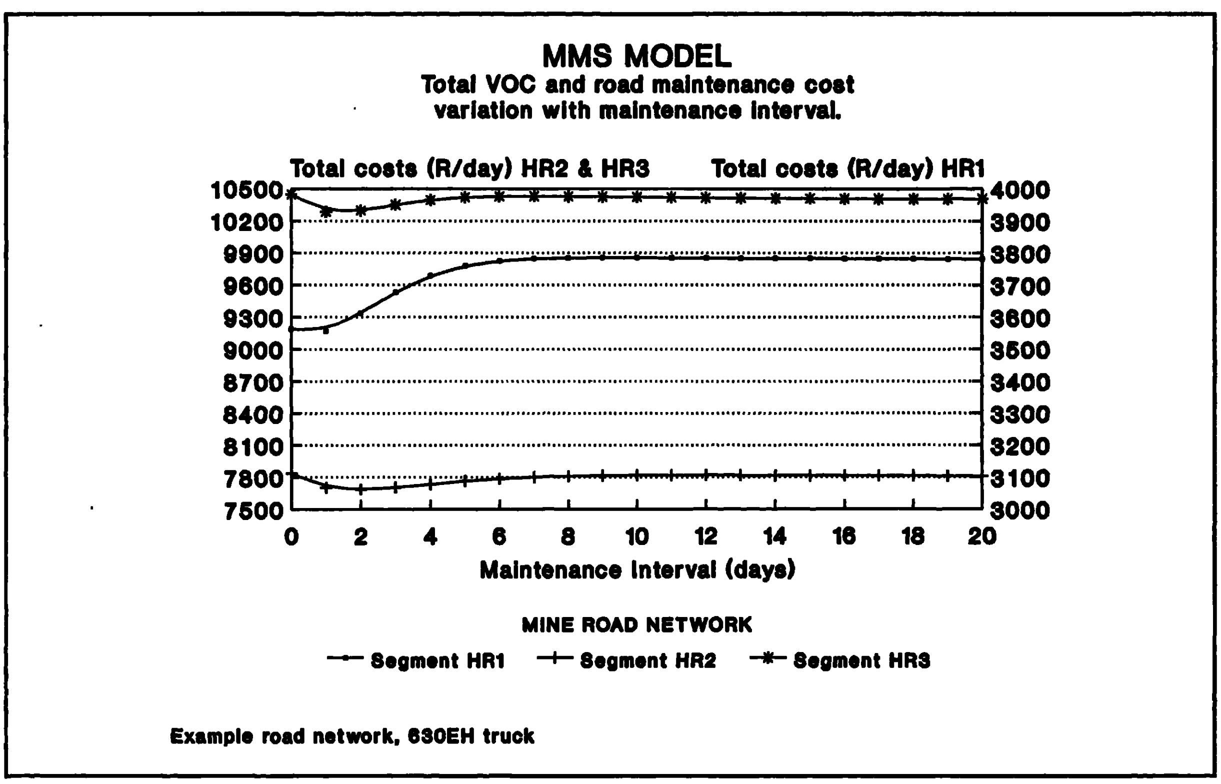


Figure 15.3 Total Segment Cost variation with Maintenance Interval

or grader hours exceeds required maintenance hours then the final solution is reported together with an indication of required grader hours as shown in Table 15.6. Whilst the final solution only utilises 32% of the available grader-hours per day, it indicates the extent to which the road-graders may be used for additional activities without detriment to optimal haul road performance.

Table 15.6 Sample Program Report For Feasible Optimal Solution

```
OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR EXAMPLE

Segment        Optimum total          Optimum maintenance
               daily cost (R)         interval (days)

Road HR1        4724.75                0
Road HR2        7687.37                2
Road HR3        10284.02               1

Feasible optimal solution.

5.97 grader hrs required per day.  18.00 grader hrs available.
Minimum total cost solution equates to a VOC and road maintenance
combined cost of R22696.15 per day.



                                          Press any key to exit
```

If required maintenance hours as dictated by the optimal maintenance interval for the various haul road segments exceeds available grader hours, an intermediate solution is given indicating the shortfall in grader operating hours associated with the cost-based optimal solution. A feasible solution is then sought from consideration of the rate of increase in total costs with increases in the maintenance interval. The road segment possessing the lowest rate of total cost change for a maintenance interval increase of one day from the optimal is selected and the maintenance interval for this segment extended by one day. The revised grader operating hours per day are recalculated for this new strategy and if less than the available hours a feasible solution is reported. If required grader hours remain in excess of available hours the process is repeated until a feasible solution is found. The cost based approach to identifying a feasible solution does not necessarily mean that segment roughness is minimised since the lowest rate of change of total costs is more likely to be associated with short, low traffic volume segments which contribute only marginally to increases in network total costs. Table 15.7 gives typical program reports from this second stage of optimisation.

Table 15.7 Sample Program Reports for Initially Infeasible Solution

```
            OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR EXAMPLE

            Segment        Optimum total              Optimum maintenance
                           daily cost (R)             interval (days)

            Road HR1        4724.75                    0
            Road HR2        7687.37                    2
            Road HR3        10284.02                   1

    Infeasible optimal solution since required grading hours per day
    exceeds available grader hours by  0.77 hrs.

            OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR EXAMPLE

            Segment        Optimum total              Optimum maintenance
                           daily cost (R)             interval (days)

            Road HR1        4729.58                    1
            Road HR2        7687.37                    2
            Road HR3        10284.02                   1

    Infeasible optimal solution since required grading hours per day
    exceeds available grader hours by  0.01 hrs.

            OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR EXAMPLE

            Segment        Optimum total              Optimum maintenance
                           daily cost (R)             interval (days)

            Road HR1        4729.58                    1
            Road HR2        7687.37                    2
            Road HR3        10297.18                   2

    Feasible optimal solution.

    4.21 grader hrs required per day.   5.20 grader hrs available.
    Minimum total cost solution equates to a VOC and road maintenance
    combined cost of R22714.14 per day.

                                                   Press any key to exit
```

15.3 Comparison of Program Results with Established Maintenance Practices

In order to compare the optimal maintenance strategy determined by the MMS model program with the established maintenance practices on the mines, analyses were undertaken for Kriel, Kromdraai, New Vaal and Kleinkopje Collieries. The data used in each model is given in Appendix P. Since Kriel, Kleinkopje and New Vaal operated mixed fleets, the assumption of a standard (Euclid R170) truck is made in these cases. Material property values are assigned to each section based on the material testing results given in Tables 3.9 to 3.12 and knowledge of the construction of the particular segment. Geometric data and traffic volumes are assigned following data in Appendix O and ramp lengths and grades have been incorporated in segment lengths where applicable.

Results of the analyses are presented in Tables 15.8-15.12 for each mine. For Kriel Colliery it is seen that for the four segments (including ramps) comprising the network, the main and ramp 7 road total costs are optimised with maintenance every other day whilst the remaining roads should be maintained every third day. This policy entails 7,06 grading hours per day which is well within the maximum available hours of 18,8 per day. Current practice at Kriel entails daily blading of the ramp areas and sections of the main haul road. Since the main haul road accounts for 65% of total daily VOC and road maintenance costs it should receive more regular maintenance. This is evident if grader hours are artificially reduced, the resultant optimal solution extending maintenance intervals on all other roads in an attempt to accommodate an optimal solution for the main haul road within the maintenance hours constraint. Total annual vehicle and road maintenance operating costs are estimated by the program at R12,66m whilst those reported by the mine are R16,59m. This difference can be ascribed primarily to the assumption of a single as opposed the mixed haul truck fleet operated at Kriel.

The results of the Kromdraai Colliery assessment (Table 15.9) also indicate a feasible optimal solution within the available grader operating hours constraint and the optimised maintenance intervals are in broad agreement with those applied by the mine, as discussed in Chapter 9.3. Estimated total annual road maintenance and vehicle operating costs of R6,18m are in broad agreement with the mine cost figure of R5,61m, the latter being based on costs assigned to

Table 15.8 Optimum Maintenance Frequency Solution for Kriel Colliery

```
        OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR KRIEL

        Segment        Optimum total               Optimum maintenance
                       daily cost (R)              interval (days)

        Main HR         29289.09                    1
        R6/10           2658.80                     2
        R7              7343.95                     1
        R8/11           5800.60                     2

 Feasible optimal solution.

 7.06 grader hrs required per day.  18.80 grader hrs available.
 Minimum total cost solution equates to a VOC and road maintenance
 combined cost of R45092.46 per day.




                                             Press any key to exit
```

Table 15.9 Optimum Maintenance Frequency Solution for Kromdraai Colliery

```
        OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR KROMDRAAI

        Segment        Optimum total               Optimum maintenance
                       daily cost (R)              interval (days)

        Main-tip        4579.93                     0
        HR2             7471.99                     2
        HR3             9990.21                     1

 Feasible optimal solution.

 5.97 grader hrs required per day.  24.60 grader hrs available.
 Minimum total cost solution equates to a VOC and road maintenance
 combined cost of R22042.14 per day.




                                             Press any key to exit
```

a single piece of equipment multiplied by total fleet numbers. Further research into more representative VOC models should reduce this discrepancy.

In the case of the Kleinkopje assessment as shown in Table 15.10, an optimum (maximum) maintenance interval of 20 days is reported for the 2A9-R8 and 2A8-R7 roads. For this type of result, the program will also report the influence of the maximum interval on total costs. Table 15.11 presents the cost reports for daily VOC, daily maintenance cost and unoptimised total daily cost for each segment. With reference to daily VOC, roads 2A9-R8 and 2A8-R7 show relatively low costs and more critically, a low rate of increase in cost as maintenance interval increases. When maintenance costs are added to VOC it is seen that the maintenance interval and associated maintenance costs exert the greatest influence over total costs and that cost is minimum at maximum maintenance interval. If daily tonnage hauled on these segments were to be increased then this result would change, emphasising the inter-relationship between traffic volumes and rate of roughness defect progression. Due to the very different haul truck fleet from that modelled, no cost comparisons are made.

Table 15.10 Optimum Maintenance Frequency Solution for Kleinkopje Colliery

OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR KLEINKOPJE

Segment	Optimum total daily cost (R)	Optimum maintenance interval (days)
Main-tip	2965.81	0
5W & ramps	8338.64	2
R13/14 & R	8268.37	1
2A-Ramp9	3573.88	2
2A9-R8	681.198	20
2A8-R7	466.53	20
3A	7013.67	1

Feasible optimal solution.

6.63 grader hrs required per day. 11.70 grader hrs available.
Minimum total cost solution equates to a VOC and road maintenance combined cost of R31308.13 per day.

A maintenance interval of 20 days is the maximum range analysed.
Maintenance at shorter interval for these sections will increase costs only marginally

Press any key to exit

Table 15.11 Segment Cost Reports for Kleinkopje Colliery (R/km)

TOTAL DAILY VOC PER SEGMENT FOR KLEINKOPJE

Days	Main-tip	SW & ramps	R13/14 &	R2A-Ramp9	2A9-R8	2A8-R7	3A
0	2914.31	8137.67	8075.71	3465.30	652.24	446.94	6851.14
1	2940.80	8175.75	8121.56	3479.20	654.93	448.80	6896.74
2	2977.03	8228.41	8184.82	3498.34	658.78	451.36	6959.13
3	3018.26	8287.77	8256.09	3520.19	663.10	454.28	7030.63
4	3056.39	8341.09	8320.17	3540.43	667.06	456.97	7097.65
5	3085.46	8380.07	8367.13	3555.82	670.04	458.98	7149.62
6	3104.54	8404.46	8396.61	3565.88	671.96	460.29	7184.30
7	3115.85	8418.28	8413.37	3571.82	673.09	461.05	7205.20
8	3122.16	8425.67	8422.36	3575.11	673.70	461.46	7217.02
9	3125.56	8429.51	8427.04	3576.87	674.03	461.69	7223.47
10	3127.36	8431.46	8429.43	3577.79	674.20	461.80	7226.92
11	3128.30	8432.45	8430.64	3578.28	674.29	461.86	7228.74
12	3128.79	8432.95	8431.25	3578.53	674.33	461.89	7229.70
13	3129.04	8433.20	8431.56	3578.66	674.36	461.91	7230.20
14	3129.18	8433.32	8431.72	3578.72	674.37	461.92	7230.47
15	3129.24	8433.38	8431.80	3578.76	674.37	461.92	7230.60
16	3129.28	8433.42	8431.84	3578.77	674.38	461.92	7230.68
17	3129.30	8433.43	8431.86	3578.78	674.38	461.92	7230.72
18	3129.31	8433.44	8431.87	3578.79	674.38	461.92	7230.73
19	3129.31	8433.44	8431.87	3578.79	674.38	461.92	7230.74
20	3129.31	8433.45	8431.87	3578.79	674.38	461.92	7230.75

TOTAL DAILY MAINTENANCE COST PER SEGMENT FOR KLEINKOPJE

Days	Main-tip	SW & ramps	R13/14 &	R2A-Ramp9	2A9-R8	2A8-R7	3A
0	51.51	330.71	293.62	226.66	143.21	96.84	233.87
1	25.76	165.36	146.81	113.33	71.60	48.42	116.93
2	17.17	110.24	97.87	75.55	47.74	32.28	77.96
3	12.88	82.68	73.41	56.66	35.80	24.21	58.47
4	10.30	66.14	58.72	45.33	28.64	19.37	46.77
5	8.59	55.12	48.94	37.78	23.87	16.14	38.98
6	7.36	47.24	41.95	32.38	20.46	13.83	33.41
7	6.44	41.34	36.70	28.33	17.90	12.11	29.23
8	5.72	36.75	32.62	25.18	15.91	10.76	25.99
9	5.15	33.07	29.36	22.67	14.32	9.68	23.39
10	4.68	30.06	26.69	20.61	13.02	8.80	21.26
11	4.29	27.56	24.47	18.89	11.93	8.07	19.49
12	3.96	25.44	22.59	17.44	11.02	7.45	17.99
13	3.68	23.62	20.97	16.19	10.23	6.92	16.70
14	3.43	22.05	19.57	15.11	9.55	6.46	15.59
15	3.22	20.67	18.35	14.17	8.95	6.05	14.62
16	3.03	19.45	17.27	13.33	8.42	5.70	13.76
17	2.86	18.37	16.31	12.59	7.96	5.38	12.99
18	2.71	17.41	15.45	11.93	7.54	5.10	12.31
19	2.58	16.54	14.68	11.33	7.16	4.84	11.69
20	2.45	15.75	13.98	10.79	6.82	4.61	11.14

UNOPTIMISED TOTAL DAILY COST PER SEGMENT FOR KLEINKOPJE

Days	Main-tip	SW & ramps	R13/14 &	R2A-Ramp9	2A9-R8	2A8-R7	3A
0	2965.82	8468.38	8369.34	3691.95	795.45	543.78	7085.01
1	2966.55	8341.11	8268.37	3592.53	726.59	497.22	7013.67
2	2994.21	8338.64	8282.69	3573.89	706.52	483.64	7037.09
3	3031.14	8370.45	8329.49	3576.86	698.90	478.49	7089.10
4	3066.69	8407.24	8378.90	3585.76	695.70	476.33	7144.42
5	3094.05	8435.18	8416.06	3593.60	693.91	475.12	7188.59
6	3111.90	8451.71	8438.56	3598.26	692.42	474.12	7217.71
7	3122.29	8459.62	8450.07	3600.15	690.99	473.15	7234.43
8	3127.89	8462.42	8454.99	3600.29	689.61	472.22	7243.00
9	3130.71	8462.58	8456.40	3599.53	688.35	471.37	7246.85
10	3132.04	8461.52	8456.12	3598.40	687.22	470.61	7248.18
11	3132.59	8460.01	8455.11	3597.17	686.22	469.93	7248.23
12	3132.75	8458.38	8453.84	3595.96	685.35	469.34	7247.69
13	3132.72	8456.82	8452.54	3594.85	684.58	468.82	7246.91
14	3132.61	8455.37	8451.29	3593.83	683.91	468.37	7246.06
15	3132.46	8454.05	8450.15	3592.92	683.32	467.97	7245.22
16	3132.31	8452.87	8449.11	3592.11	682.80	467.62	7244.43
17	3132.16	8451.80	8448.17	3591.38	682.33	467.30	7243.71
18	3132.02	8450.85	8447.32	3590.72	681.92	467.02	7243.04
19	3131.89	8449.98	8446.55	3590.12	681.54	466.77	7242.44
20	3131.77	8449.19	8445.86	3589.59	681.20	466.53	7241.89

The results of the New Vaal Colliery assessment are given in Table 15.12 from which it is seen that the main haul road segment costs are optimised with daily maintenance. This is due in most part to the high traffic volumes experienced by these sections of road. As traffic volume decreases, the optimal maintenance interval increases on those roads carrying less traffic. This is in broad agreement with the observations made in Chapter 9.3 in which it was seen that the maintenance intervals applied at New Vaal were largely in response to anticipated traffic volumes as available production moved from ramp to ramp. As a result of the traffic volume experienced on the road, a large increase in the roughness defect score is seen which, at high maintenance intervals, reduces grader productivity. This effect is shown in Table 15.13, the upper limit on roughness defect score being 47 for road M-tip-R0.

Table 15.12 Optimum Maintenance Frequency Solution for New Vaal Colliery

OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR NEW VAAL

Segment	Optimum total daily cost (R)	Optimum maintenance interval (days)
M-tip-R0	11351.53	0
MR0-R2	18667	0
MR2-R3	8797.16	0
MR3-R4	4077.14	0
MR4-R6/7	3795.02	1
MR6/7-R9	2317.30	3
R0	5314.19	1
R2	1999.56	2
R3	2710.01	2
R4	605.34	20

Feasible optimal solution.
7.11 grader hrs required per day. 23.10 grader hrs available.
Minimum total cost solution equates to a VOC and road maintenance combined cost of R59634.28 per day.
A maintenance interval of 20 days is the maximum range analysed.
Maintenance at shorter interval for these sections will increase costs only marginally Press any key to exit

The examples addressed here are based on average annual data supplied by each mine and as such reflect the optimum policy for these particular conditions. Coal production is dynamic in the sense that traffic volumes on various segments of the network change as coal production areas move. Further benefit may be realised when the MMS is applied in

Table 15.13 Maintenance Fleet Productivity, New Vaal Colliery

MAINTENANCE FLEET PRODUCTIVITY.

Days	Reqd km/day	Graded km/day	Watered km/day
0	8.364	17.32	1514.93
1	4.182	17.32	1514.93
2	2.788	17.32	1514.93
3	2.091	17.32	1514.93
4	1.673	17.32	1514.93
5	1.394	17.32	1514.93
6	1.195	17.30	1514.93
7	1.046	17.29	1514.93
8	0.929	17.29	1514.93
9	0.836	17.28	1514.93
10	0.760	17.28	1514.93
11	0.697	17.28	1514.93
12	0.643	17.28	1514.93
13	0.597	17.28	1514.93
14	0.558	17.28	1514.93
15	0.523	17.28	1514.93
16	0.492	17.28	1514.93
17	0.465	17.28	1514.93
18	0.440	17.28	1514.93
19	0.418	17.28	1514.93
20	0.398	17.28	1514.93

Hit any key to continue

conjunction with monthly production planning, so as to identify any changes in the optimal maintenance policy as planned production areas change. Whilst these results generally reflect current maintenance practices on the mines, it is also important to determine the sensitivity of total and segment costs to varying sub-optimal maintenance strategies.

15.4 Sensitivity of Maintenance Strategy to Model Parameters

Total vehicle operating and road maintenance costs have been seen to vary with maintenance interval as discussed in Section 15.3. Whilst the optimum maintenance frequency was identified for each mine haul road segment, no indication was given of the cost trade-offs due to departure from the optimal schedule. An indication of the cost of sub-optimal maintenance intervals on segment and network total costs can be assessed from the program segment cost reports similar to those presented in Table 15.11.

Figure 15.4 illustrates the change in daily operating cost for each segment of the Kromdraai Colliery road. As can be seen, total costs decrease as the optimal intervals are approached for each section of road. In this particular case, the rate of change of costs for both under- and over-maintaining the road are approximately similar, by virtue of the cost of maintenance and segment total VOC's being similar. This situation would change as tonnage hauled varies as depicted in Figure 15.5. In this analysis, a single segment (HR3) of the Kromdraai Colliery road network is subjected to increasing traffic volumes and the maintenance interval and rate of change of total (segment) cost is seen to vary as the VOC component increases with tonnage hauled.

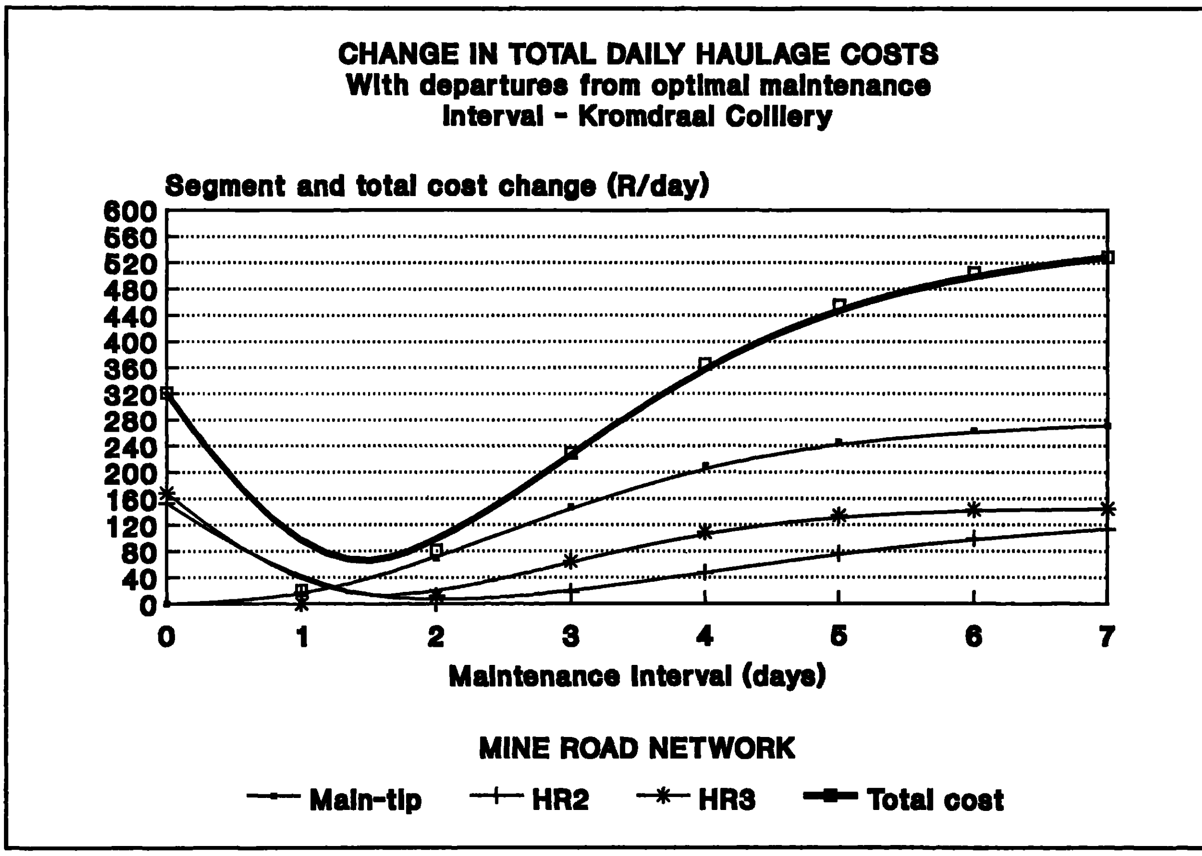


Figure 15.4 Total Daily Haulage Cost Variation with Maintenance Interval - Kromdraai Colliery

Similar effects are seen for Kriel (Figure 15.6) and Kleinkopje (Figure 15.7). In the case of New Vaal Colliery, if sub-optimal maintenance strategies are adopted, total costs are seen only to rise. This is a result of the combination of high tonnages and associated daily maintenance regimes on the heavy traffic sections of road. Full results are given in Table 15.14 for each segment of the New Vaal Colliery haul road network. If maintenance intervals are reduced by a day for those roads with a optimum interval of one day or more, annual total costs are seen to increase by R9 375. However, if an extra day is added to the

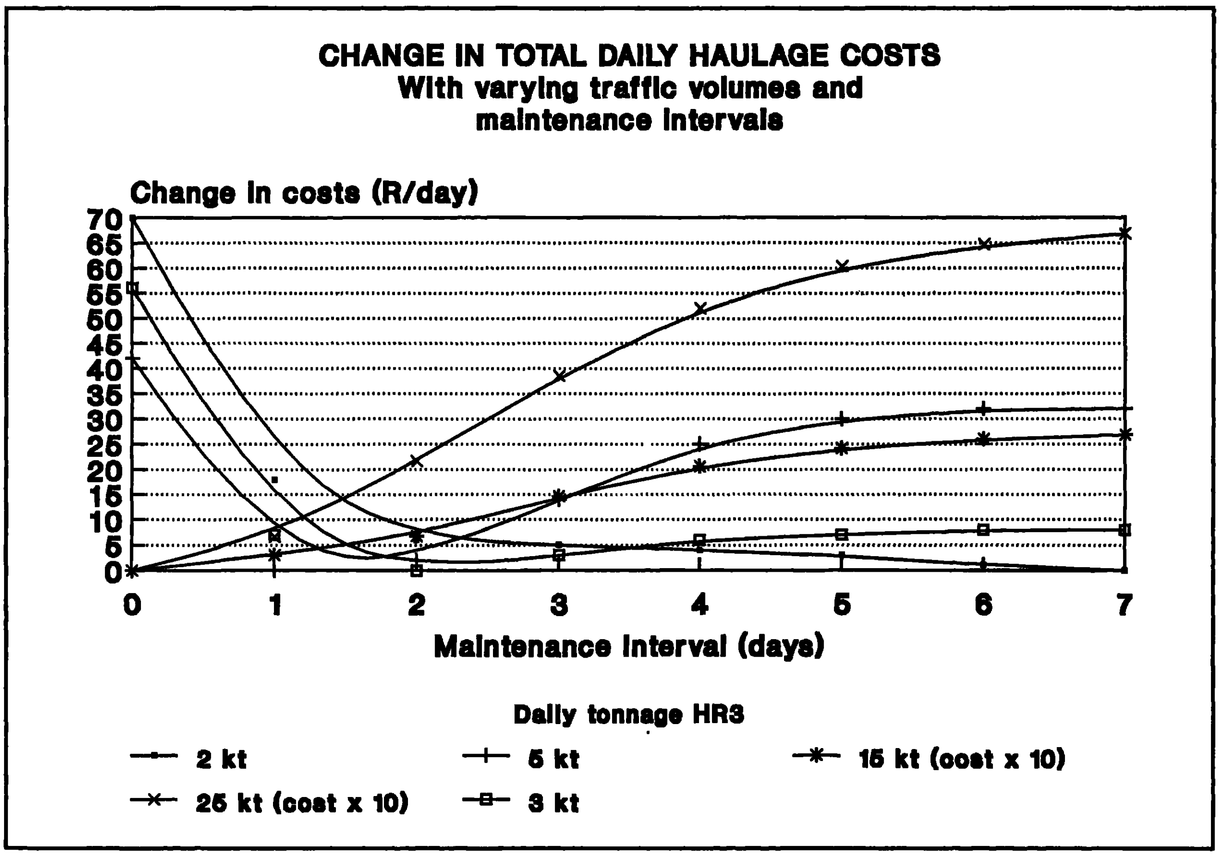


Figure 15.5 Effect of Traffic Volumes on Segment Daily Costs

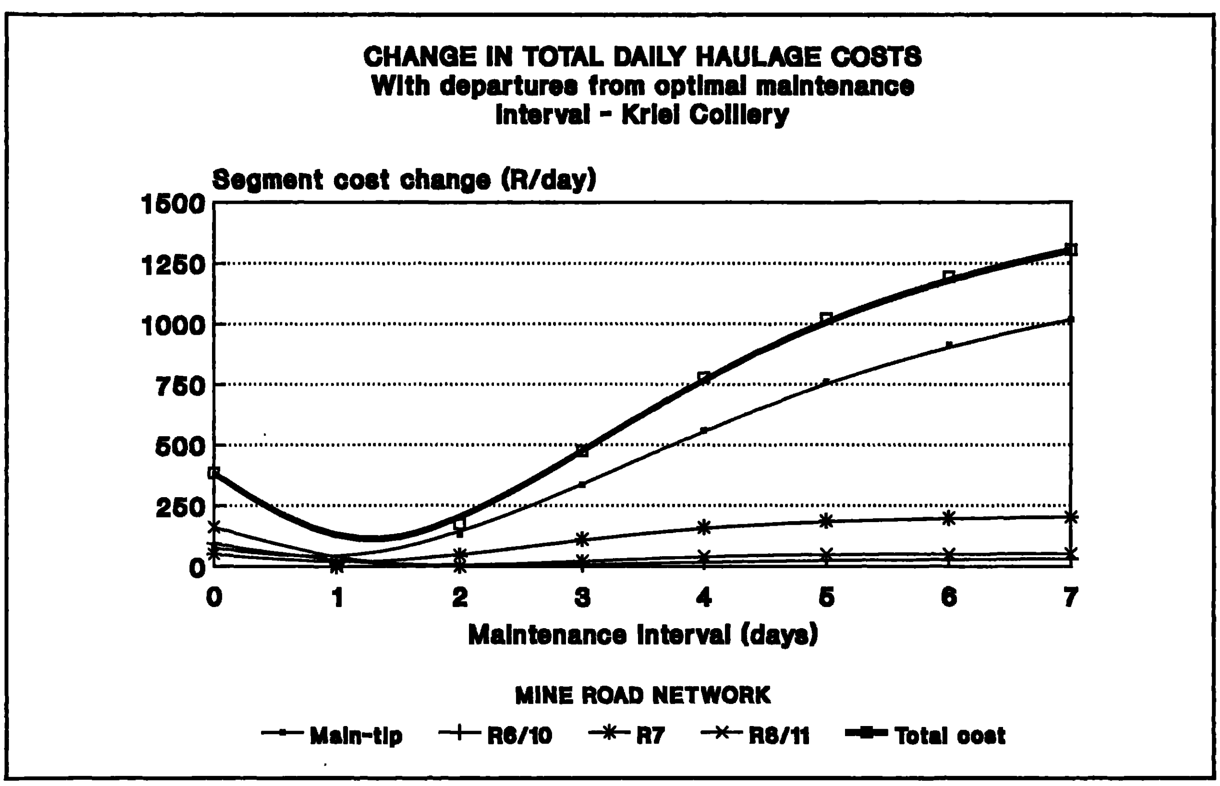


Figure 15.6 Total Daily Haulage Cost Variation with Maintenance Interval - Kriel Colliery

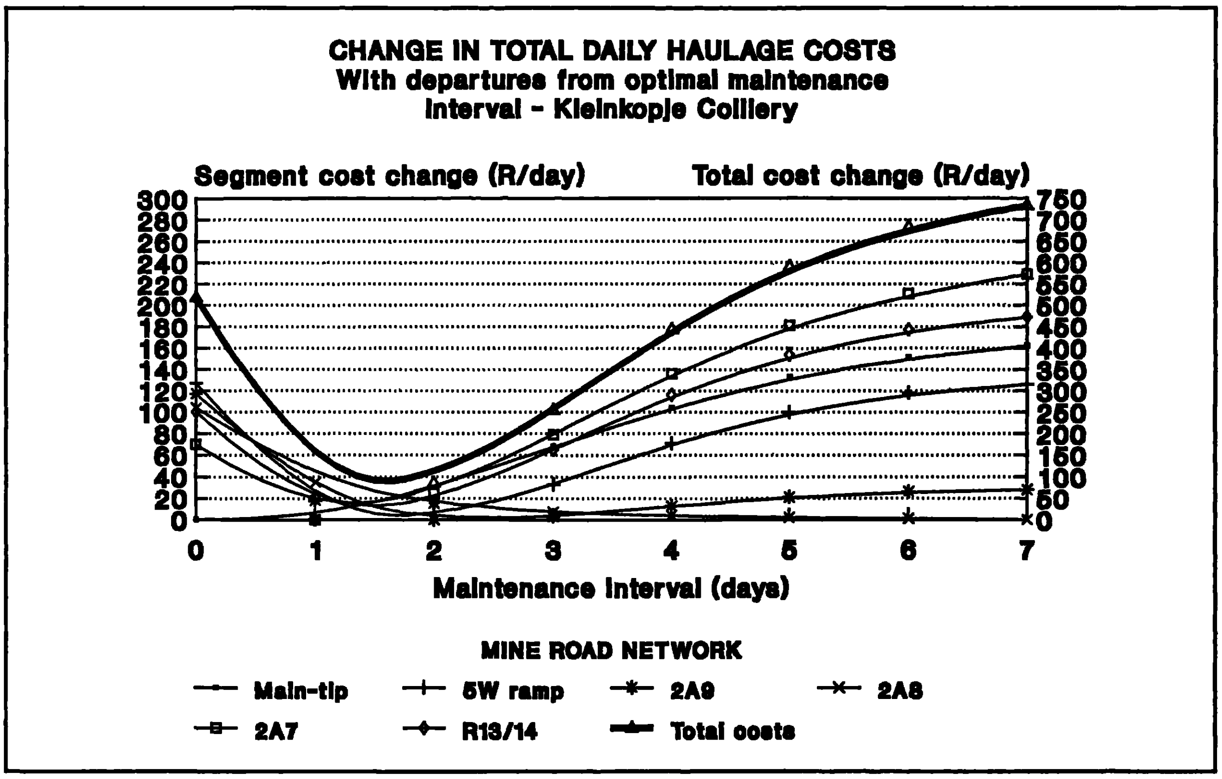


Figure 15.7 Total Daily Haulage Cost Variation with Maintenance Interval - Kleinkopje Colliery

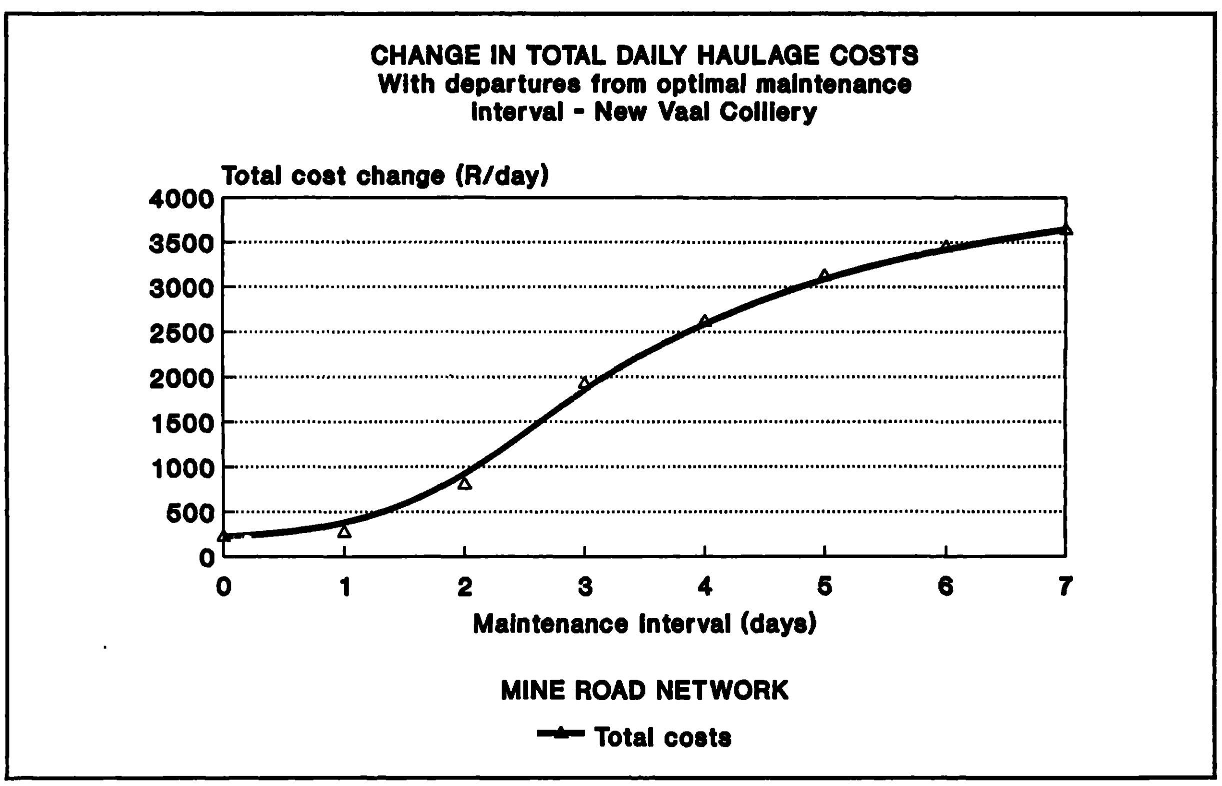


Figure 15.8 Total Daily Haulage Cost Variation with Maintenance Interval - New Vaal Colliery

Table 15.14 Total VOC and Road Maintenance Cost Increases Associated with Sub-optimal Maintenance Intervals - New Vaal Colliery

SEGMENT TOTAL DAILY VOC AND ROAD MAINTENANCE COST VARIATION WITH INCREASING AND DECREASING MAINTENANCE INTERVALS

Maintenance Interval	HAUL ROAD SEGMENT TOTAL COST (R)										Annual savings (R)
	M-tip-R0	MR0-R2	MR2-R3	MR3-R4	MR4-R6/7	MR6/7-R9	R0	R2	R3	R4	
Optimum	11351,53	18667,00	8797,16	4077,14	3795,02	2317,30	5314,19	1999,56	2710,01	605,34	-
+ 1 day	11490,23	18817,77	8841,87	4078,09	3808,12	2320,09	5335,67	2004,21	2719,02	-	108520
+ 2 day	11705,64	19104,70	8956,26	4116,13	3832,42	2323,25	5322,47	2010,40	2723,83	-	312237
- 1 day	-	-	-	-	3815,22	2317,99	5368,24	2000,24	2713,53	0,04	9375

optimal maintenance interval of each segment, annual total VOC and road maintenance costs for the network are seen to increase by R108 520 and for an interval of 2 days beyond optimal, annual costs increase by R312 237. Depending on the specific mine haul route characteristics, the MMS system has the potential to generate significant cost savings.

15.5 Summary and Conclusions

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 VOC and road maintenance. Models comprising these cost components, developed in previous chapters, were included in the program to determine road roughness, rolling resistance, vehicle speed, fuel, tyre and parts consumption costs and labour hours. Road maintenance costs and fleet productivity was assessed by means of user specified data in conjunction with a basic grader productivity model. The limitations in the application of these best estimate models should be borne in mind when analysing the results presented by the model.

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. When analysing the results of individual mine simulations, the actual mine operating practice was seen to closely resemble that predicted by the model, especially with regard to increased maintenance intervals on lightly trafficked roads. In all cases, available grader hours was found to be considerably more than the operating hours required for the optimal policy. The total costs predicted by the program were found to be in broad agreement with cost data supplied by the mine, bearing in mind the assumptions necessary in modelling each haul truck fleet and the exclusion of additional road maintenance activities.

From an analysis of the rate of change in VOC and road maintenance costs for individual segments with increases and decreases in the optimal maintenance interval, a sub-optimal maintenance interval incorporating too infrequent maintenance was seen to be associated with excessive costs. The rate of change of costs for both under- and over-maintaining the road were found to be a function of the cost of maintenance and segment total VOC's. Increasing traffic volumes result in more frequent maintenance and the penalties associated with over-maintenance of the road are seen to decrease in significance compared to the rate of increase in costs associated with under-maintenance of tue road. It is concluded that the adoption of the MMS model program for mine haul roads has the potential to generate significant cost savings when used dynamically in conjunction with production planning.

CHAPTER 16
CONCLUSIONS AND RECOMMENDATIONS

16.1 Conclusions

The primary objective of the research was the development of a portable and practical haul road design and management technique that encompassed both pavement strength and operating performance considerations. These performance characteristics were subdivided into structural, functional and maintenance design categories. The primary objectives addressed within each design category were;

- The prediction of mine haul road structural performance through the use of analytical models and the recommendation of a formal mechanistic structural design procedure which encompasses typical mine haul road vehicle loads and available construction material properties.
- The development and analysis of material selection guidelines for use in haul road functional design together with recommendation of selected wearing course material parameter ranges to fulfil road-user defined mine haul road functional performance requirements.
- Through an analysis of pavement deterioration rates and maintenance cost/road quality relationships, the development of vehicle operating and pavement performance models for incorporation in a maintenance management system for surface mine haul roads.

16.1.1 Structural Design

The optimal mechanistic structural design of a surface mine haul road embodies 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. In addition, of the various design options analysed, the inclusion of a rock layer immediately below the wearing course proffered the structure increased resilience to the applied loads without recourse to excessive structural thickness.

The derivation of limiting design criteria for the mechanistic design of surface mine haul roads was based on a structural performance categorisation of mine haul roads. Stresses and strains generated from a multi-layer elastic solution for each road test section were compared with the structural performance categorisation to establish suitable design criteria. Construction material elastic moduli were assessed in terms of both the TRH14 and TRH20 classification and the DCP derived empirical relationship whereby suitable moduli for the various classes of granular materials used in haul road construction were derived.

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 structural performance of the road; those mine sites exhibiting poor performance and an associated excessive maximum deflection were seen to be associated with large vertical compressive strain values in one or more layers. It was found that an upper limit of 2000 microstrain should be placed on layer strain values, this value being associated with typical traffic volumes and required degree of structural performance. Strain values exceeding this value have been shown to be associated with unacceptable structural performance. 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 material grading, Atterberg limits, CBR, swelling and field compaction characteristics. This catalogue-type approach assists in the practical application of the method where road building materials, essentially similar to those analysed, are encountered 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 ranged from 17MPa to 388MPa. The use of DCP derived 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, thereby reducing deflections in the lower layers to a minimum. 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, it was found that the proposed optimal design provided an improved structural response to the applied loads in comparison to thicker CBR based design and, in addition, did not contravene any of the proposed limiting design criteria for the particular traffic type, volume and required degree of performance. 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.

16.1.2 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. The commonality between typical defects reported for unpaved public roads and the functionality requirements for mine haul roads indicated that existing specifications for unpaved public road wearing course construction materials would form a suitable base for the development of specifications for mine haul roads. A qualitative functional performance assessment methodology was developed based on typical haul road wearing course, formation and function defects in order to assess the utility of established performance related wearing course selection guidelines and as a basis for revised functional performance parameter specifications.

From the functionality assessment exercise it was found that the 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 high prediction errors associated with the model were ascribed to the variability in both the defined and undefined independent variables which control defect progression rates. However, the applicability of the model is limited by the relatively small inference space of the data and where materials are encountered which differ significantly from those assessed during the test work, judgement and care should be exercised when applying the predicted results. In determining suitable wearing course material selection guidelines this work confirmed the earlier qualitative observations that grading and plasticity parameters would adequately anticipate the functional performance of a wearing course material.

The development of acceptability criteria for haul road functionality fulfilled a deficiency identified in the literature review. In addition to assigning acceptability ranges to each type of defect, the impact and accident potential of each defect was categorised and ranked according to the total impact and accident potential on the components of hauling, namely operation, truck and tyre. 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 and that the consequences, in terms of the possible generation of these defects, should therefore be incorporated into any suitable selection criteria established for mine haul road wearing course materials.

The derivation of wearing course material selection guidelines was based on the identification, characterisation and ranking of haul road functional defects. A reference framework was developed within which suitable specifications should fall, based on an assessment of the requirements of good specifications in the light of functional defect ranking and acceptability limits. The TRH20 wearing course material selection guidelines were found to be a suitable source for the specification of mine haul road wearing course material parameter requirements. A revised range of 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. By analysing the trends evident in the individual defect rankings, the predictive capability of the specification was enhanced by depicting the variation in functional defects which would arise when departures are made from recommended parameter limits.

16.1.3 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. Maintenance design concerns the optimal frequency of wearing course maintenance commensurate with minimum vehicle operating and road maintenance costs. 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. The road roughness progression model forms the basis of the MMS since roughness is the principal measure of pavement condition that can be directly related to both vehicle operating costs and the frequency of maintenance activities.

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. To facilitate portability and comparison of the qualitative assessment technique, expressions were developed to enable direct comparison to be made between roughness defect score and IRI. 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 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. Based on the tentative similarity between experimentally derived rolling resistance model values for mine haul road roughness and those reported in the literature it was proposed that the models derived to describe rolling resistance variation with road roughness be provisionally adopted in the MMS model. However, to fully characterise the effect of road roughness attributes on ultra-heavy haul trucks it is recommended that an investigation be undertaken specifically using these trucks.

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 combination of these models enabled the optimal maintenance strategy to be sought based on the minimisation of these costs over a particular haul route. The fuel consumption model development was based on the simulation of typical coal haulage trucks used by the mines. The similarity in speed versus total resistance performance of these trucks prompted the development of four universal equations by means of which vehicle speed could be predicted for any combination of total resistance and truck loading. The constant speed fuel consumption model was used as an explanatory variable in the fuel consumption model in which equations were developed for the fuel consumed by trucks on both favourable and unfavourable total resistance segments of a haul route. The verification of the models to actual mine data proved problematic since no fuel consumption test data was found with which to validate the models. An approximate fuel consumption figure was deduced from mine operating records and vehicle annual ton-kilometres which showed good agreement with the model when applied over a similar haul route. It is recommended however, that on-site fuel consumption tests be conducted with which to rigorously verify the fuel consumption models adopted.

With regard to the tyre, vehicle maintenance parts and maintenance labour models developed, similar data limitations were seen which 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. These models were then compared with the limited mine data available to verify the order of magnitude of the costs modelled and, more critically, to indicate the likely rate of change of these costs with road roughness. The latter proved particularly problematic due to data characteristic limitations and it is recommended that further research be conducted to assess the validity and transferability of the basic models proposed.

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. Road maintenance costs and fleet productivity was assessed by means of user specified data in conjunction with a basic grader productivity model. The limitations inherent in the development and application of these models should be borne in mind when analysing the results presented by the model.

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. When analysing the results of individual mine simulations, the 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. From an analysis of the rate of change in vehicle operating and road maintenance costs for individual segments with reductions in the frequency of maintenance beyond the optimal maintenance interval, these 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.

16.2 Recommendations

The development of a portable and practical haul road design and management technique was addressed in this thesis. During its development, assumptions had to be made regarding aspects of structural, functional and maintenance management designs which were beyond the scope or feasibility of this research project. Whilst some hypotheses postulated were in general agreement with the available data, verification in a wider inference space is desirable, as is the development of relationships describing certain mine haul-truck and -road interactions. Specific recommendations are:

- To test the hypothesis that if the optimal mechanistic design for mine haul roads is adopted, the primary mode of road deterioration is related to the functional performance of the wearing course materials.

- To confirm the hypothesis that contact stresses under a ultra-heavy haul truck wheel can be reliably predicted from tyre inflation pressures and the assumption of circular contact areas.

- To determine if the vertical compressive strains recorded in each layer of a haul road designed according to the mechanistic structural methodology correlate with those predicted from a multi-layer elastic solution using the recommended material effective elastic modulus selection parameters and limiting design criteria.

- To perform additional studies to validate and extend the inference sphere of the various models developed to predict individual and combined functional defect progression rates.

- To fully characterise the effect of road roughness attributes on ultra-heavy haul truck rolling resistance.

- To test the validity of the fuel consumption equations developed for mine haul trucks through a combined series of road roughness/rolling resistance and fuel consumption tests on a selection of mine roads.

- To develop rigorous road grader productivity relationships which relate at least to road roughness defect score before blading.

- To develop applicable road-user cost relationships that would eliminate the need to adopt road roughness and cost relationships from other studies in which key parameter ranges are not directly comparable. For reliable application, these relationships should cover the widest range of road roughnesses available and include an appropriately designed data collation exercise for each cost component.

16.3 Implementation

The implementation of the new design and management techniques developed for mine haul roads is desirable in determining the practical advantages and disadvantages of the structural, functional and maintenance management methods proposed. Limited implementation of the structural design recommendations has occurred, but a rigorous evaluation of the method, in which predicted and actual pavement layer vertical compressive strains are assessed, is required for comprehensive verification of the methodology.

The recommended wearing course material selection parameters need to be assessed in practice together with the proposed functionality progression models. The implementation of these selection parameters on a number of operating mines would also permit the verification of the models over a wider inference space and resultant feedback would facilitate adjustments of the models to more reliably accommodate lower quality materials.

The maintenance management system developed for mine haul roads reflects closely the current operating practices on a number of mines. Implementation of the system on operating mines will provide the opportunity to assess the practicality of the optimum maintenance schedules proposed and the applicability of the roughness defect progression models upon which the optimisation of maintenance is based.

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APPENDICES

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CONTENTS

APPENDIX A

SELECTED WEARING COURSE MATERIAL SPECIFICATIONS FOR MINE HAUL ROADS

Haul Road Material Selection Specifications from Kaufman and Ault (1977).

SCREEN ANALYSIS (%) PASSING	
75.00mm	100
63.00	100
53.00	100
37.50	100
26.50	98
19.00	92
13.20	82
4.75	65
2.00	53
0.425	33
0.075	16[A]
CONSTANTS	
Grading modulus	-
Dust ratio	-
Liquid limit	≤25
Plasticity index	≤10
Linear shrinkage (%)	-
Max dry density (kg/m^3)	-
OMC (%)	12
MMC (%)	-
Dry density (kg/m^3)	-
% Max dry density	-
100% Mod CBR	80
% Swell	-
Wearing course thickness	150mm

A Kaufman and Ault suggest a minimum of 5% fines for hot, dry conditions to prevent drying and loosening and a maximum of 10% fines for wet conditions to reduce slipperiness and cutting-up of the wearing course.

Haul Road Material Selection Specifications from Fung (1981). Adapted from AASHTO M147-65 standard specification for materials for aggregate and soil-aggregate subbase, base and surface courses.

SCREEN ANALYSIS (%) PASSING	
75.00mm	-
63.00	-
53.00	-
37.50	-
26.50	100
19.00	-
13.20	-
9.75	50-85
4.75	35-65
2.00	25-50
0.425	15-30
0.075	8-15
CONSTANTS	
Grading modulus	-
Dust ratio	>0,66
Liquid limit	≤35
Plasticity index	≤4-9
Linear shrinkage (%)	-
Max dry density (kg/m^3)	-
OMC (%)	-
MMC (%)	-
Dry density (kg/m^3)	-
% Max dry density	-
100% Mod CBR	80
% Swell	-
Wearing course thickness	-

Haul Road Material Selection Specifications from McInnes (1982). Adapted from the Standards Association of Australia (NAASRA, 1974) specification for pavement materials (part 2) for natural gravels, sand-clay and soft and fissile rock.

SCREEN ANALYSIS (%) PASSING	A
75.00mm	-
63.00	-
53.00	-
37.50	-
26.50	-
19.00	55
13.20	-
9.75	-
4.75	-
2.00	≤30
0.425	-
0.075	-
CONSTANTS	
Grading modulus	-
Dust ratio	-
Liquid limit	≤35
Plasticity index	≤4-15[B]
Linear shrinkage (%)	≤6
Max dry density (kg/m^3)	-
OMC (%)	-
MMC (%)	-
Dry density (kg/m^3)	-
% Max dry density	-
100% Mod CBR	60
% Swell	-
Aggregate pliers value (%)	20
Wearing course thickness	150

[A] McInnes presents details of grading requirements in terms of a grading envelope similar to Olmstead's chart together with similar functionality defect descriptions for materials outside the suggested grading envelope. Olmstead's chart for mechanically stable mixtures is presented overleaf.

[B] Suggested values for gravel and soft rock. If enough gravel fraction present, McInnes proposes PI may be extended upto 25. Sand-clays limited to low rainfall regions (<400mm) and a PI of 5-15.

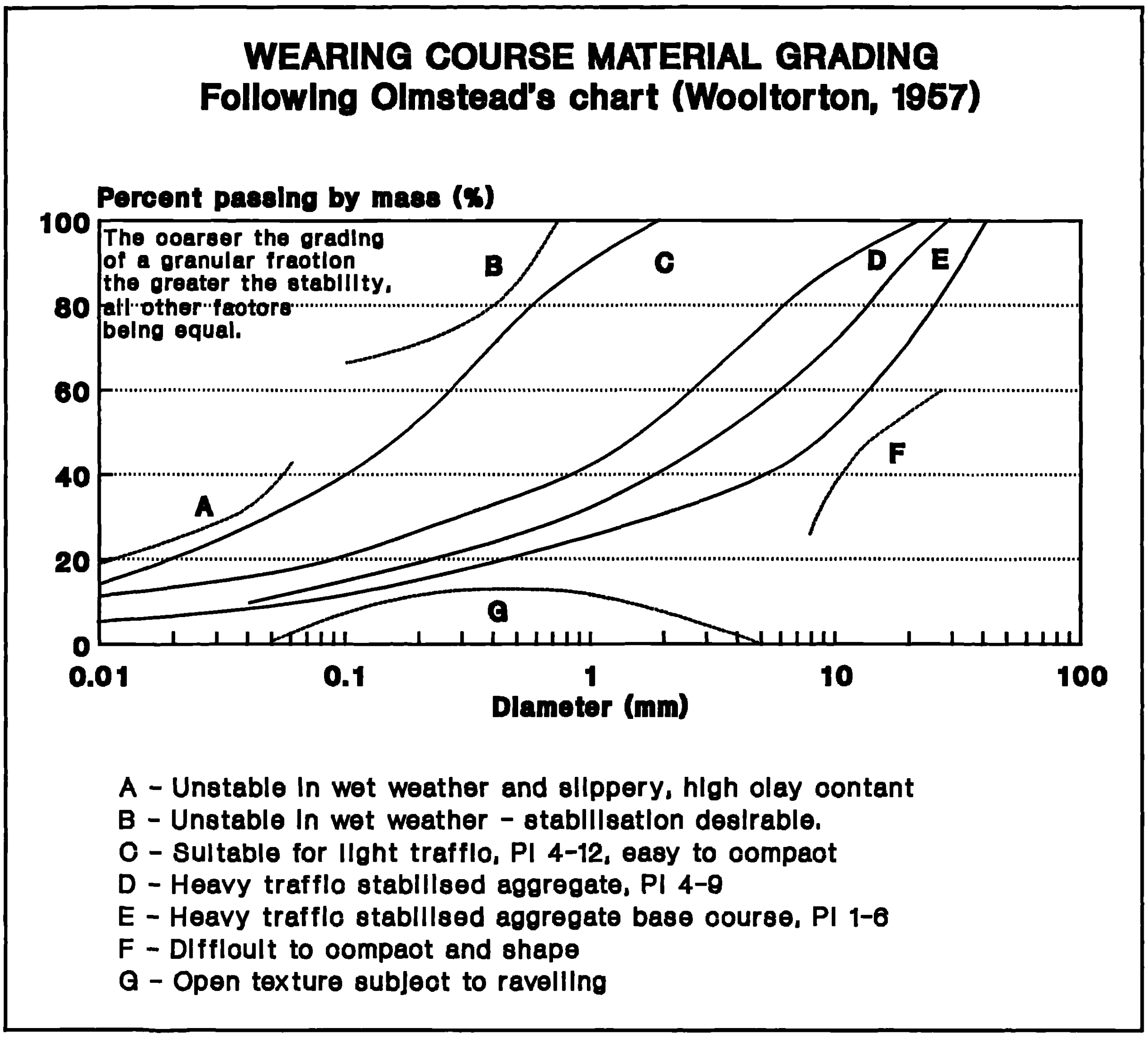


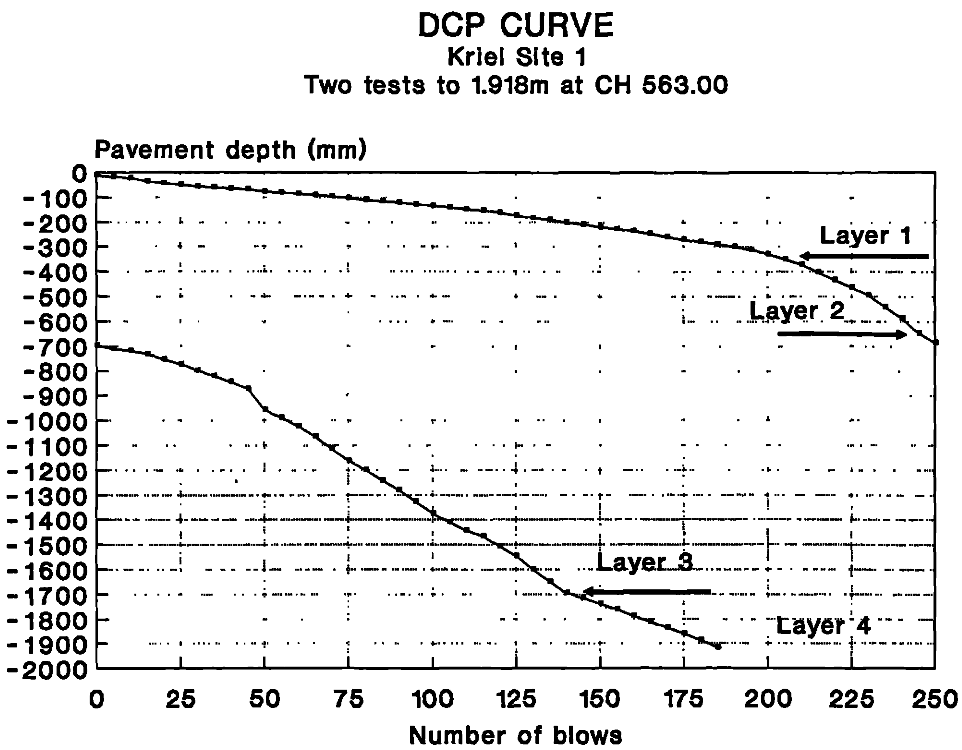
Figure 1 Olmstead's chart for suitable wearing course material grading envelopes.

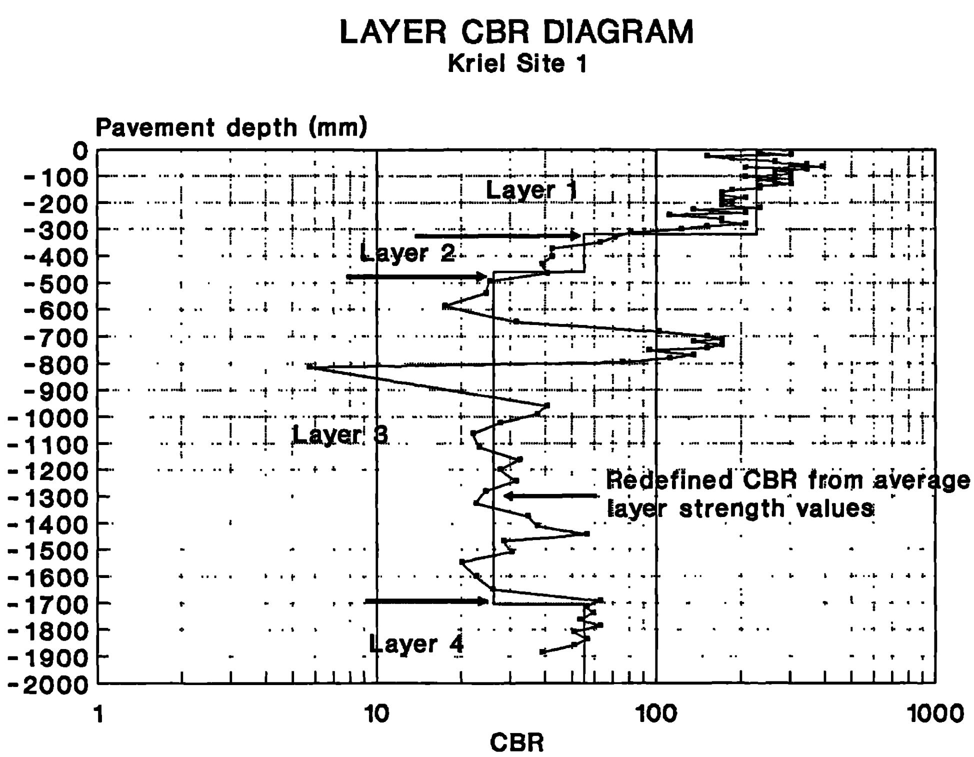
APPENDIX B

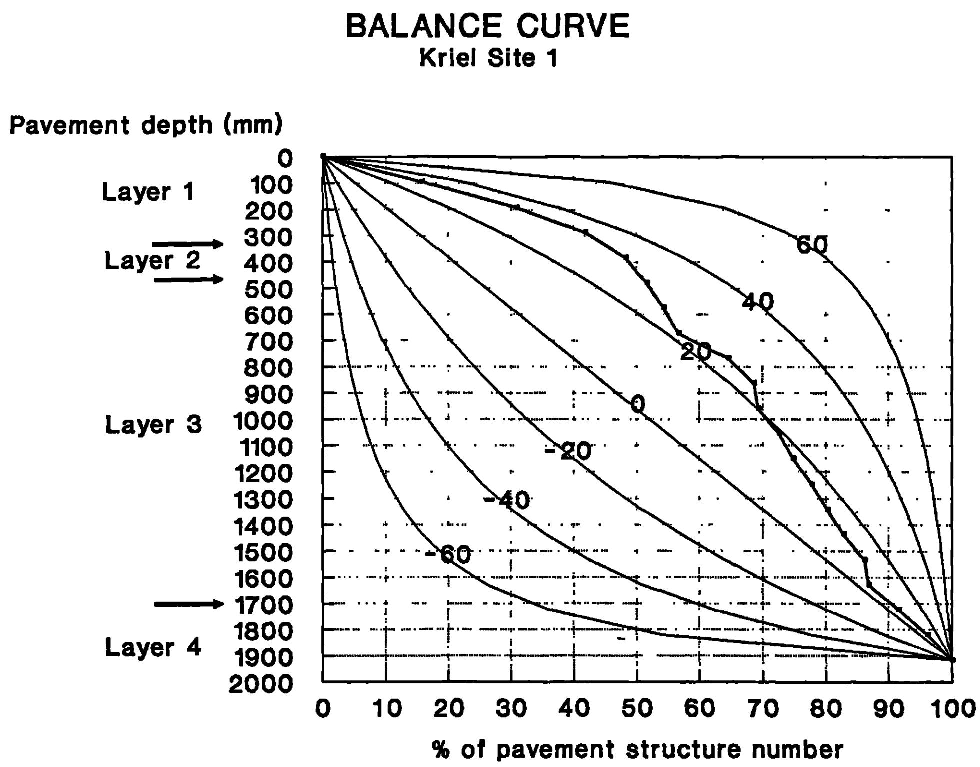
DYNAMIC CONE PENETROMETER ANALYSIS OF PAVEMENT STRUCTURES

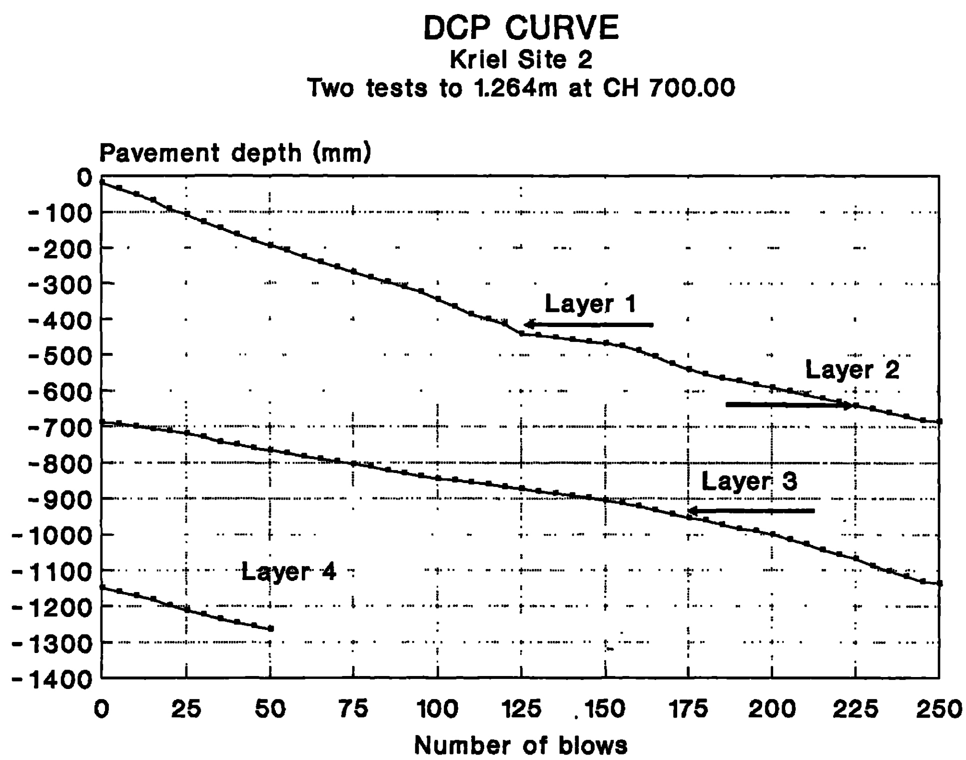
Contents

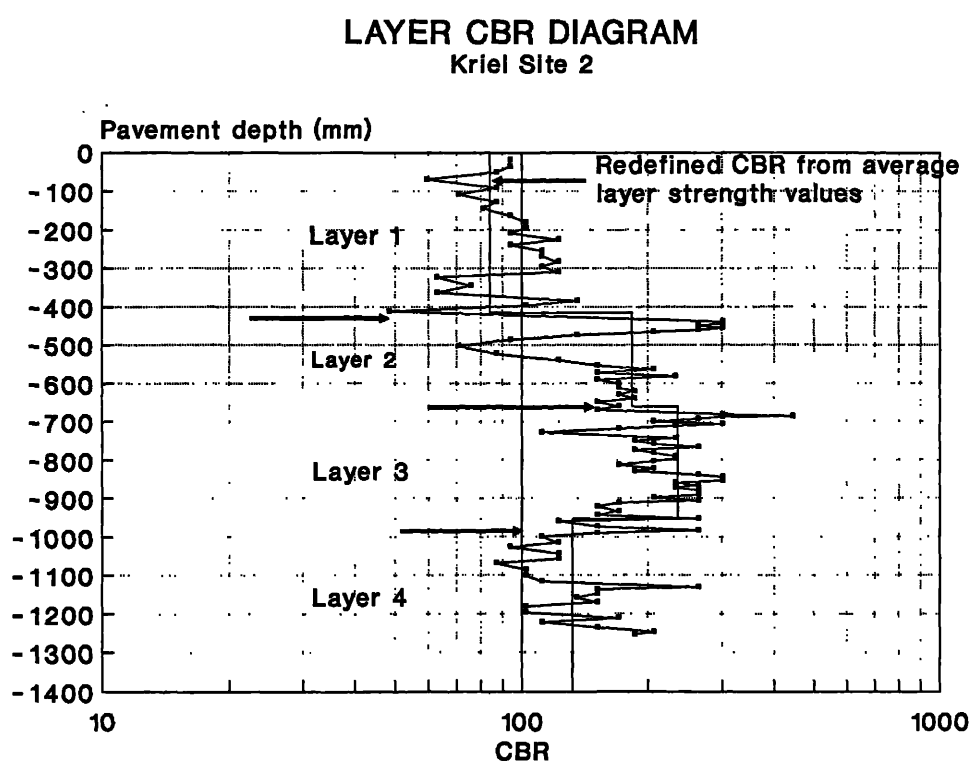
For Kriel, Kromdraai and New Vaal Colliery test sites 1, 2 and 3.

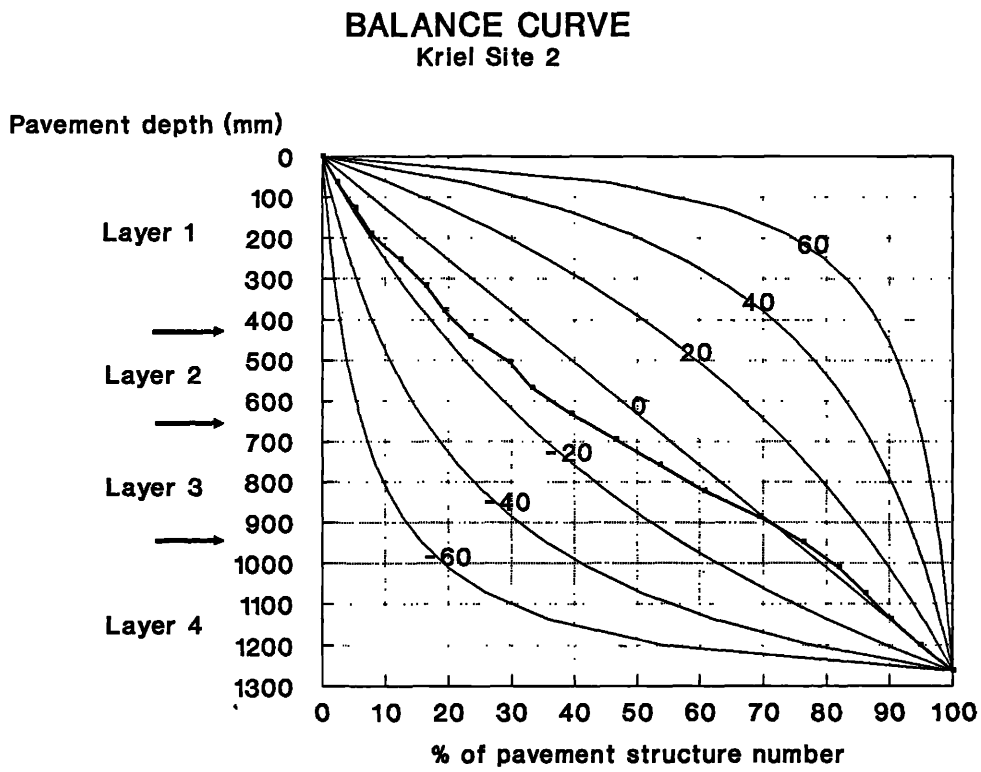

DCP CURVE
Kriel Site 1
Two tests to 1.918m at CH 563.00
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
Number of blows

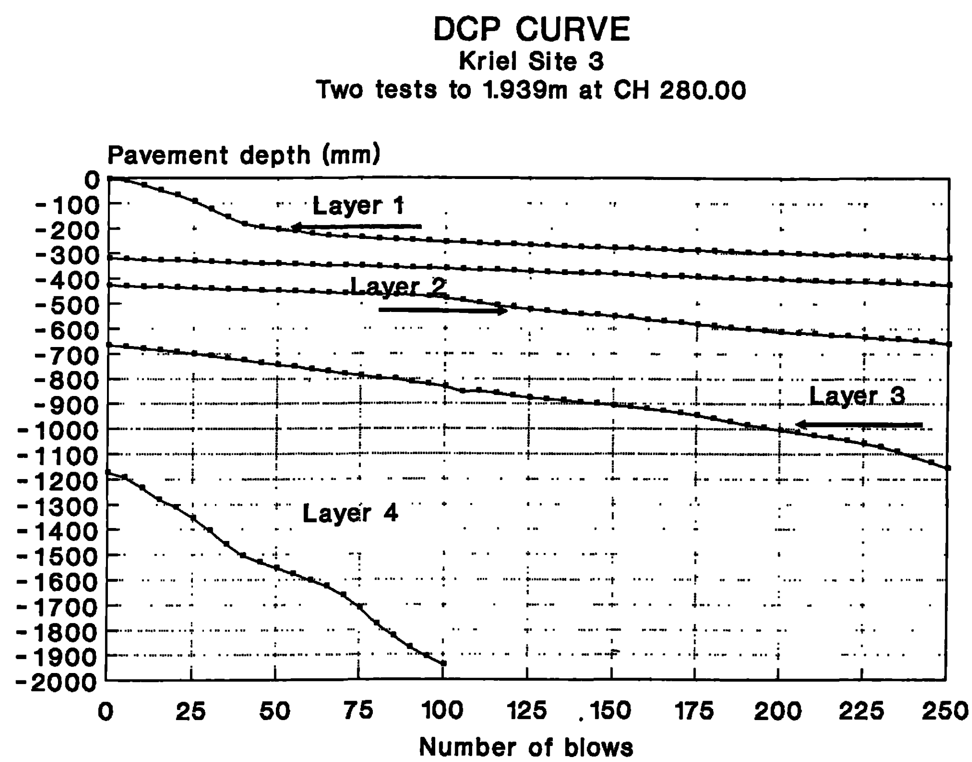

LAYER CBR DIAGRAM
Kriel Site 1
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Redefined CBR from average layer strength values
Layer 4
CBR

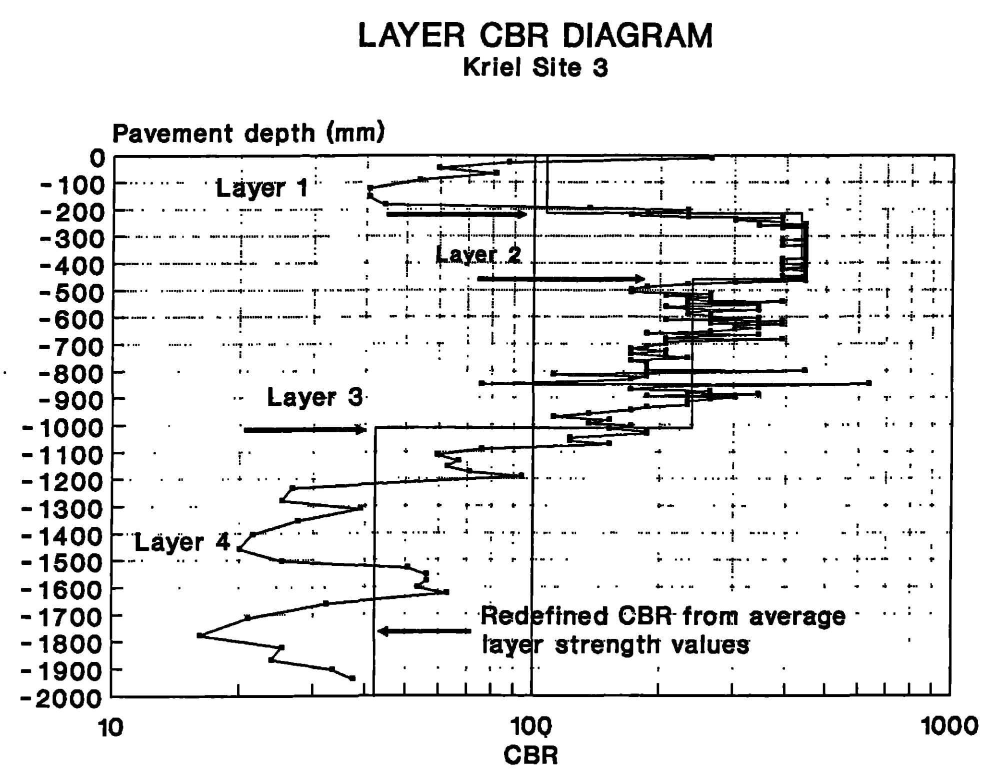

BALANCE CURVE
Kriel Site 1
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
60
40
20
0
-20
-40
-60
0 10 20 30 40 50 60 70 80 90 100
% of pavement structure number

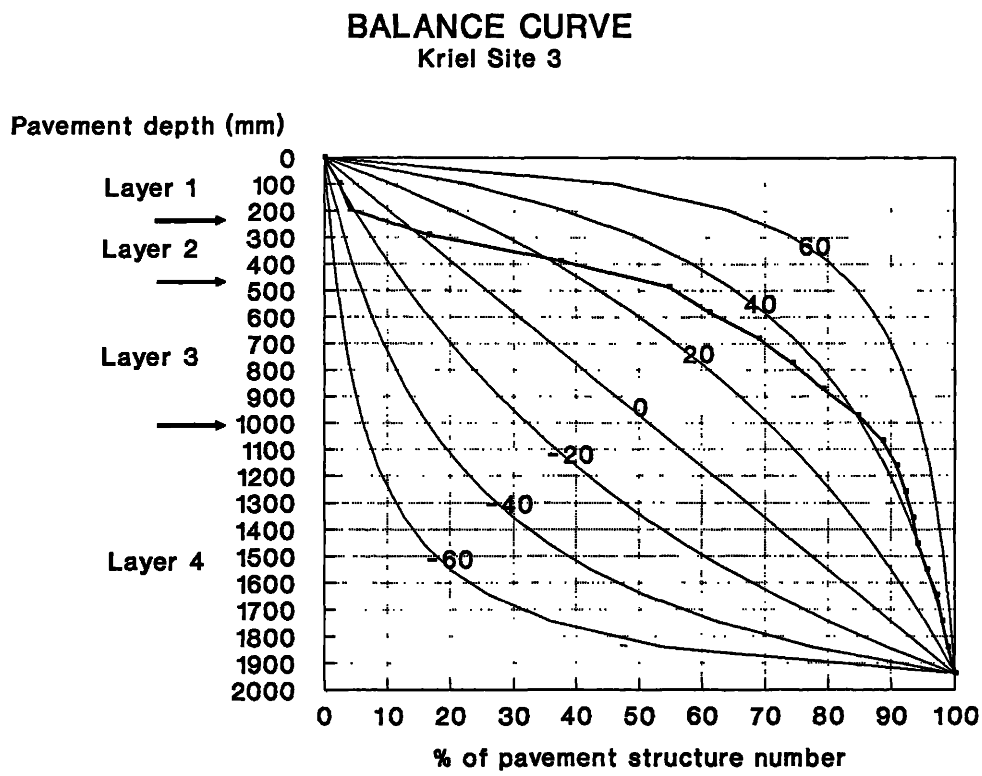

DCP CURVE
Kriel Site 2
Two tests to 1.264m at CH 700.00
Pavement depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
Layer 1
Layer 2
Layer 3
Layer 4
0
25
50
75
100
125
150
175
200
225
250
Number of blows

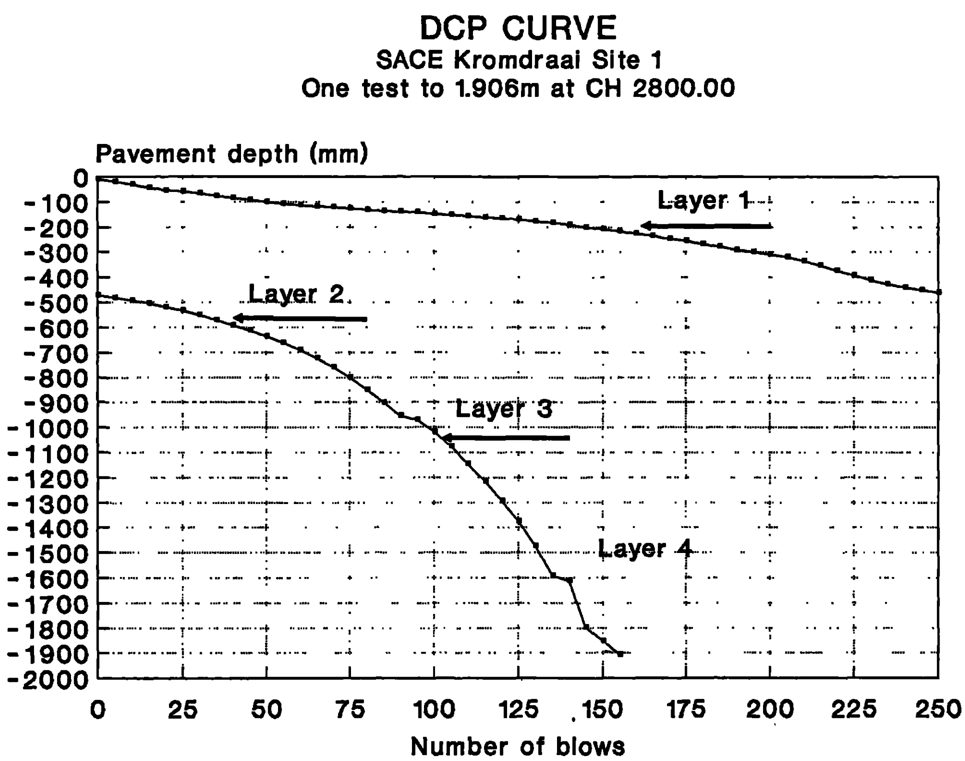

LAYER CBR DIAGRAM
Kriel Site 2
Pavement depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
Redefined CBR from average
layer strength values
Layer 1
Layer 2
Layer 3
Layer 4
10
100
1000
CBR

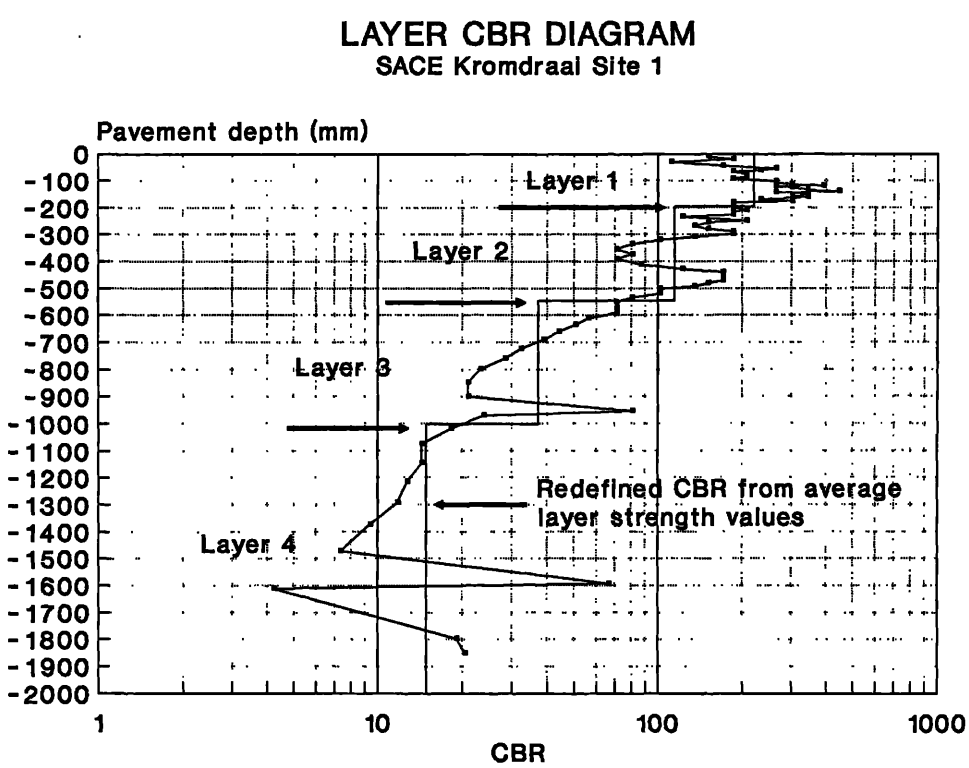

BALANCE CURVE
Kriel Site 2
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
60
40
20
0
-20
-40
-60
0
10
20
30
40
50
60
70
80
90
100
% of pavement structure number

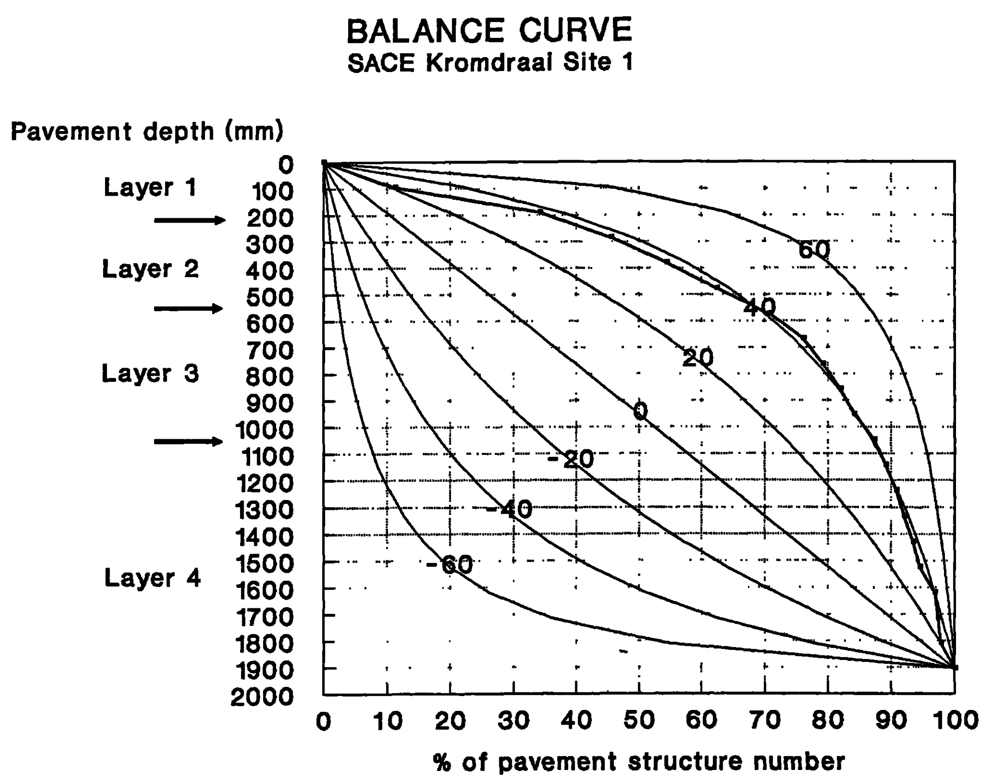

DCP CURVE
Kriel Site 3
Two tests to 1.939m at CH 280.00
Pavement depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
-1600
-1700
-1800
-1900
-2000
Layer 1
Layer 2
Layer 3
Layer 4
0
25
50
75
100
125
150
175
200
225
250
Number of blows

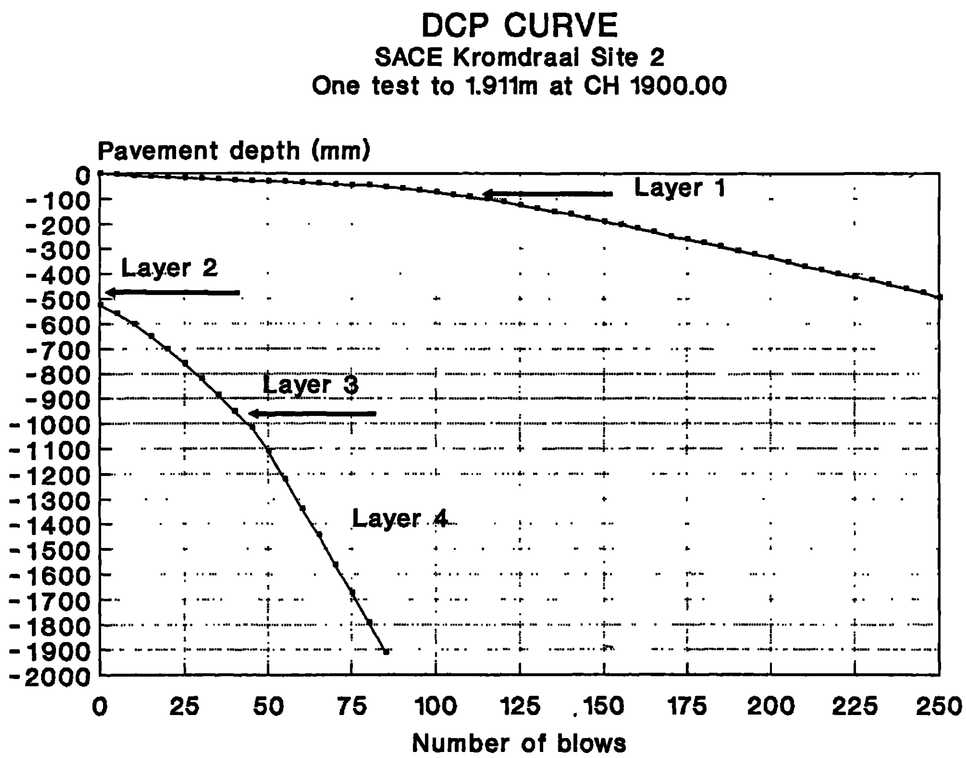

LAYER CBR DIAGRAM
Kriel Site 3
Pavement depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
-1600
-1700
-1800
-1900
-2000
Layer 1
Layer 2
Layer 3
Layer 4
Redefined CBR from average
layer strength values
10
100
1000
CBR

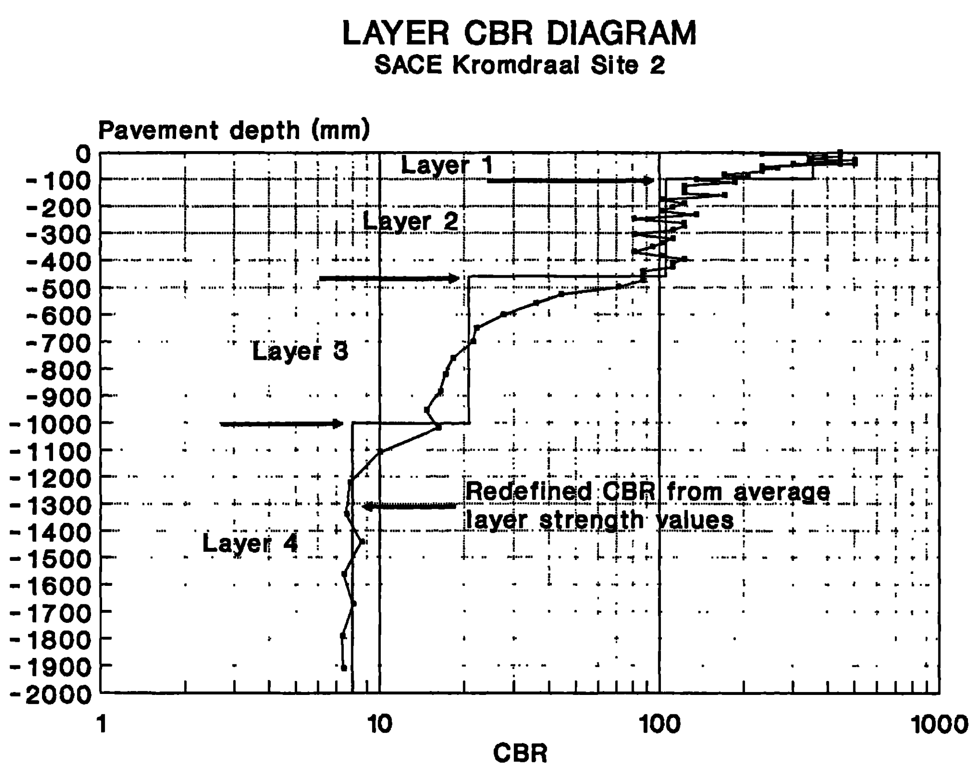

BALANCE CURVE
Kriel Site 3
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
60
40
20
0
-20
-40
-60
0
10
20
30
40
50
60
70
80
90
100
% of pavement structure number

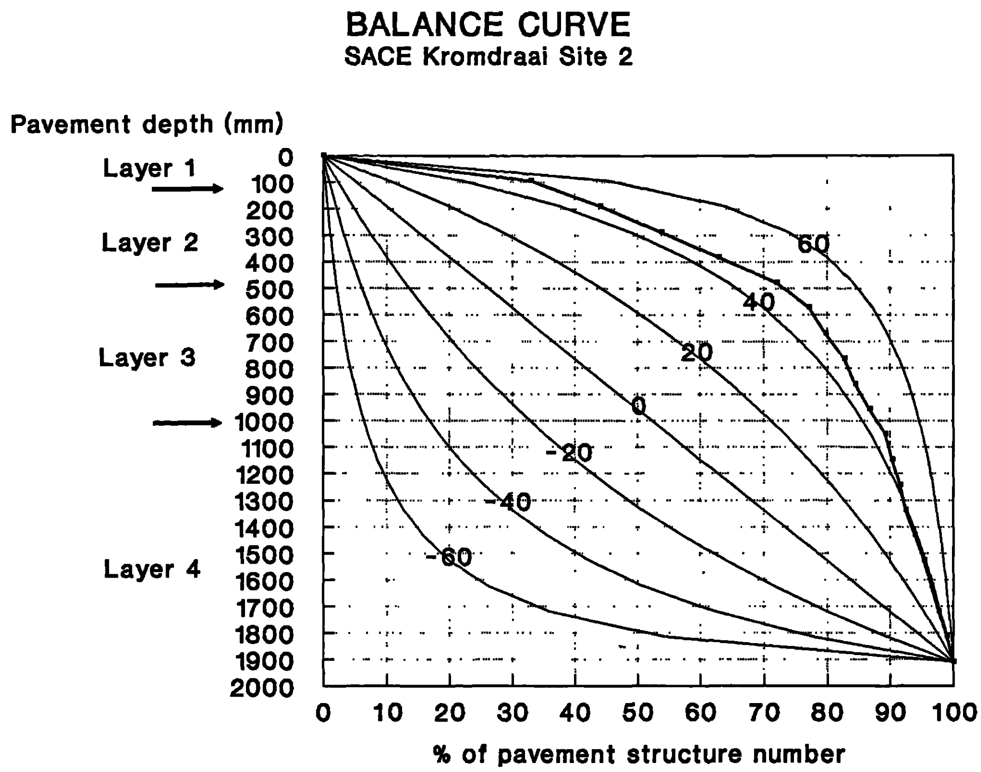

DCP CURVE
SACE Kromdraai Site 1
One test to 1.906m at CH 2800.00
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
-1600
-1700
-1800
-1900
-2000
0
25
50
75
100
125
150
175
200
225
250
Number of blows

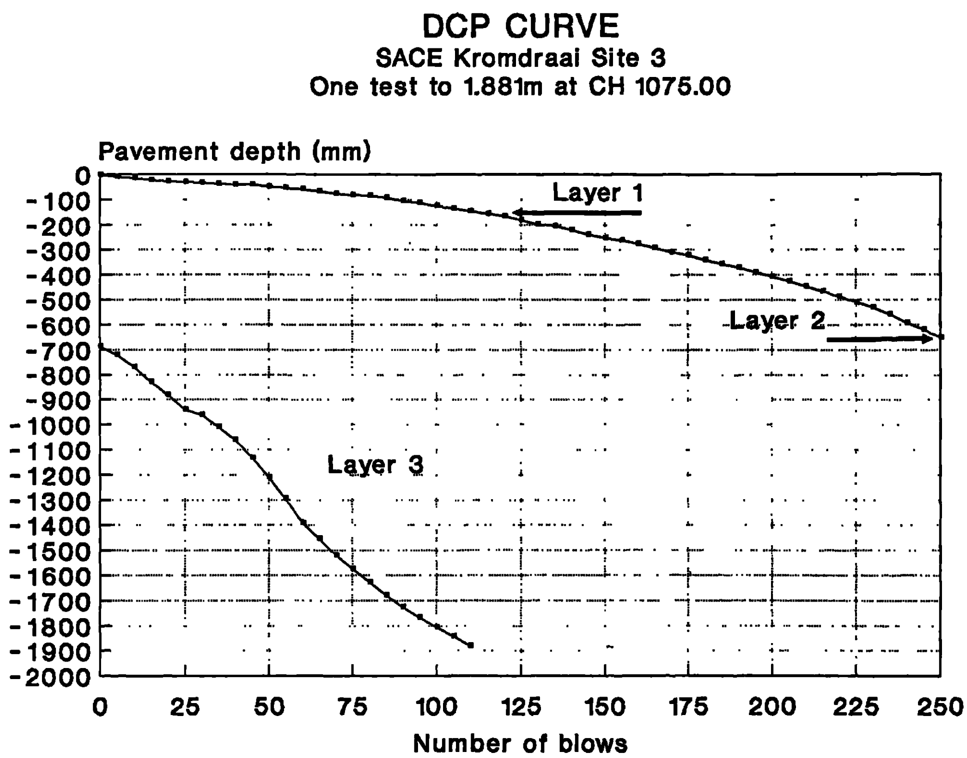

LAYER CBR DIAGRAM
SACE Kromdraai Site 1
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
Redefined CBR from average layer strength values
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
-1600
-1700
-1800
-1900
-2000
1
10
100
1000
CBR

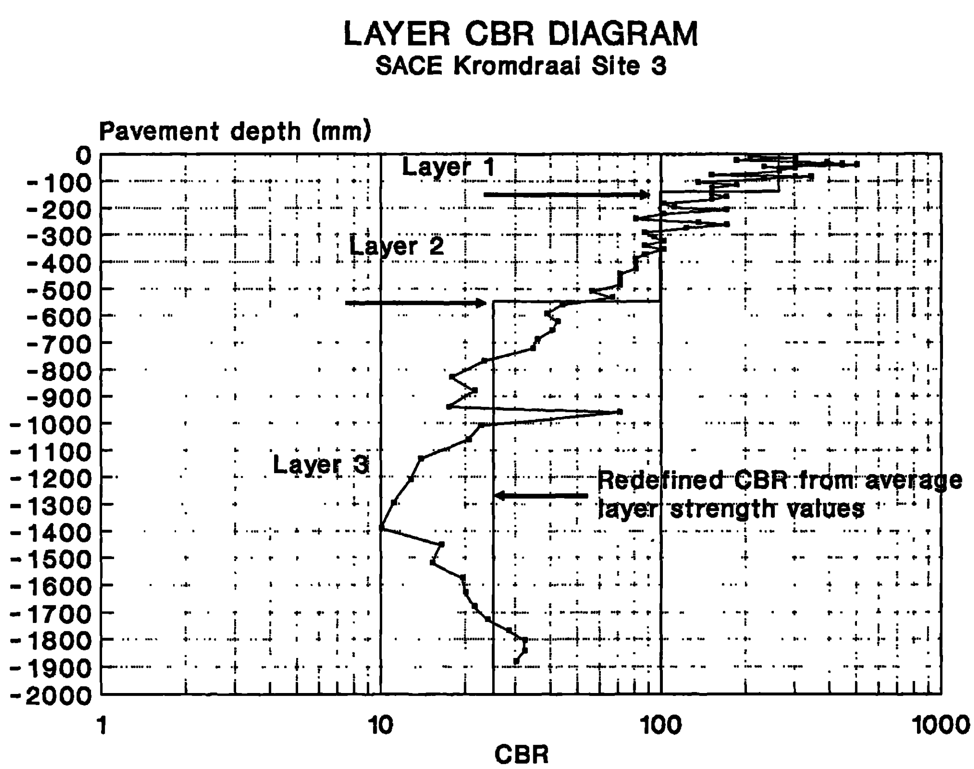

BALANCE CURVE
SACE Kromdraai Site 1
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
0 10 20 30 40 50 60 70 80 90 100
% of pavement structure number
60
40
20
0
-20
-40
-60

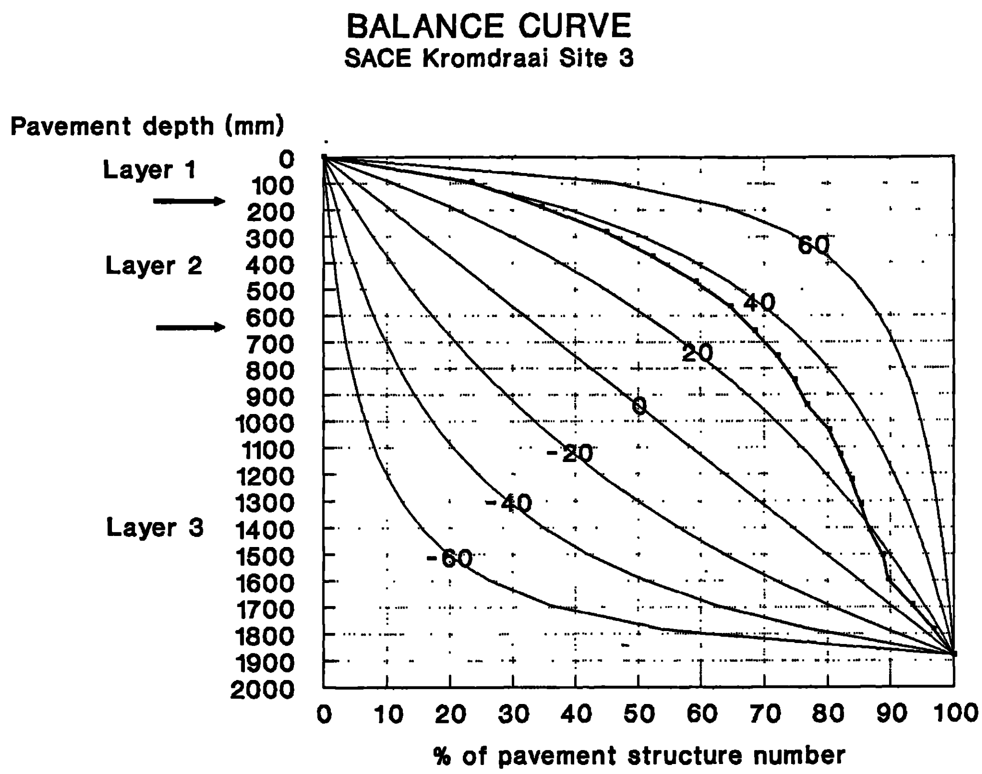

DCP CURVE
SACE Kromdraal Site 2
One test to 1.911m at CH 1900.00
Pavement depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
-1600
-1700
-1800
-1900
-2000
Layer 1
Layer 2
Layer 3
Layer 4
0
25
50
75
100
125
150
175
200
225
250
Number of blows

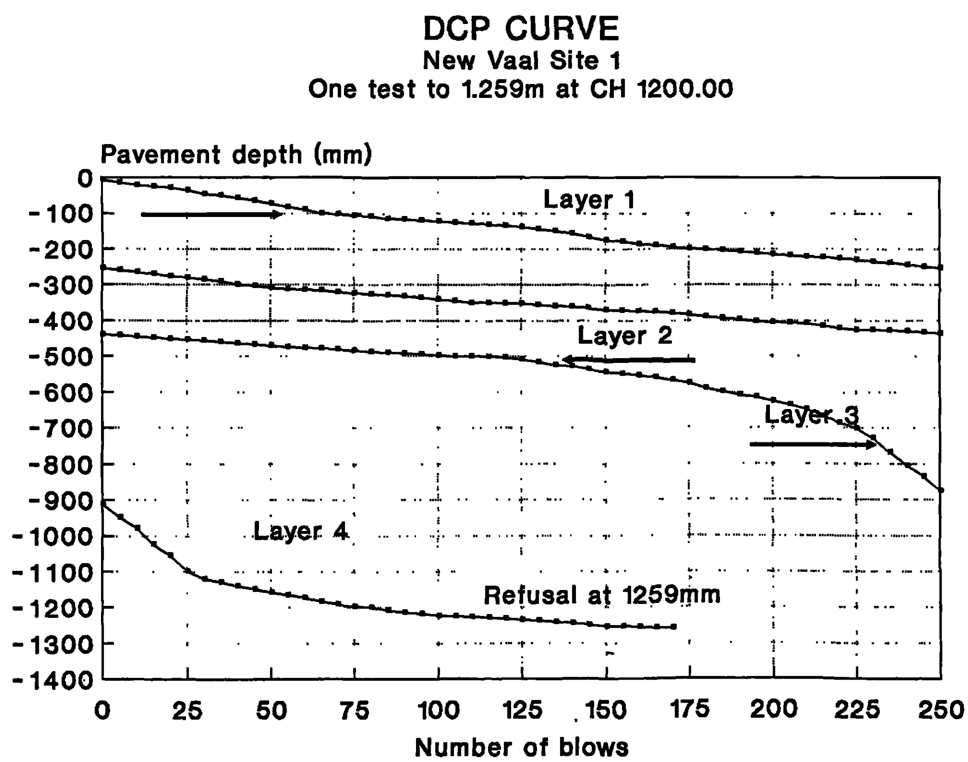

LAYER CBR DIAGRAM
SACE Kromdraal Site 2
Pavement depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
-1600
-1700
-1800
-1900
-2000
Layer 1
Layer 2
Layer 3
Layer 4
Redefined CBR from average
layer strength values
1
10
100
1000
CBR

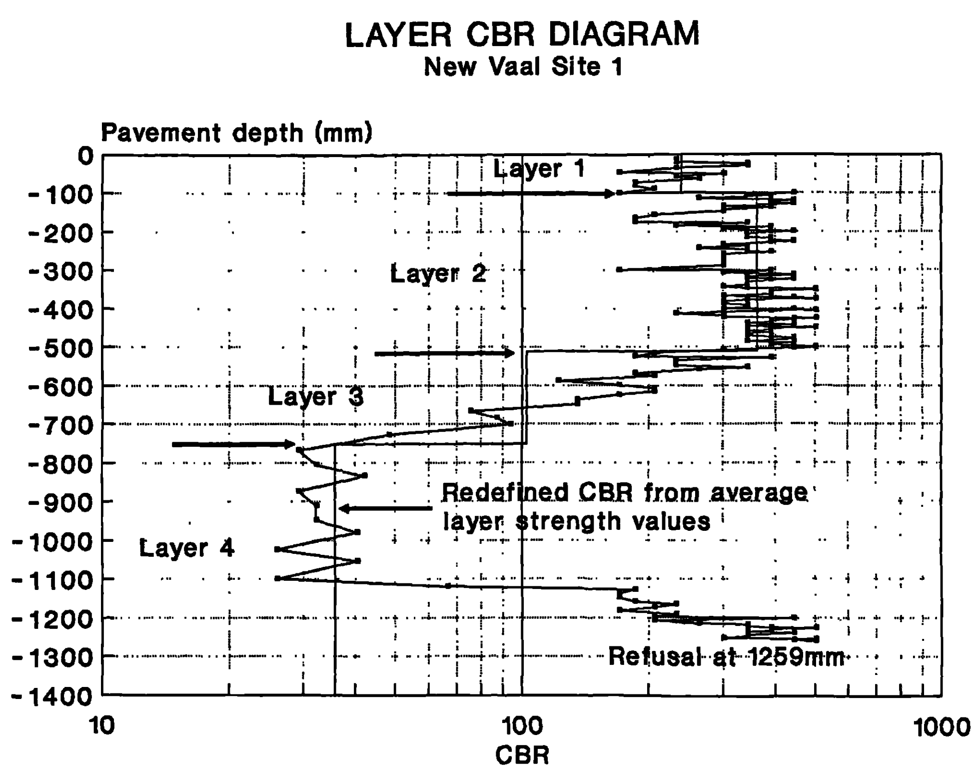

BALANCE CURVE
SACE Kromdraai Site 2
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
60
40
20
0
-20
-40
-60
0 10 20 30 40 50 60 70 80 90 100
% of pavement structure number

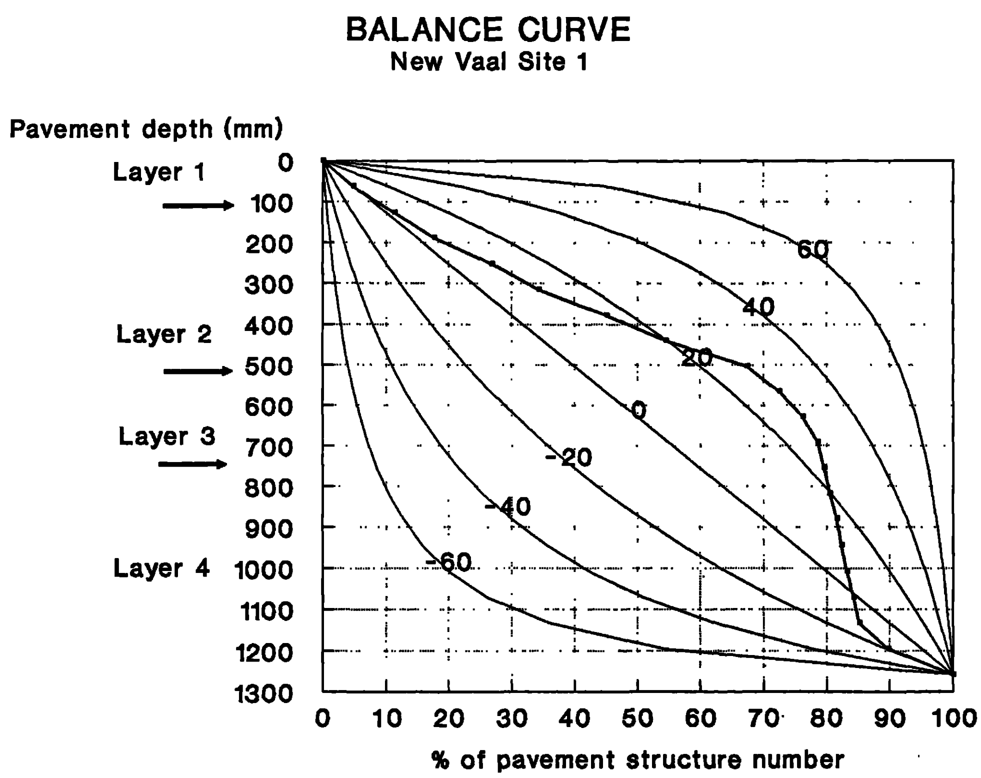

DCP CURVE
SACE Kromdraai Site 3
One test to 1.881m at CH 1075.00
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Number of blows

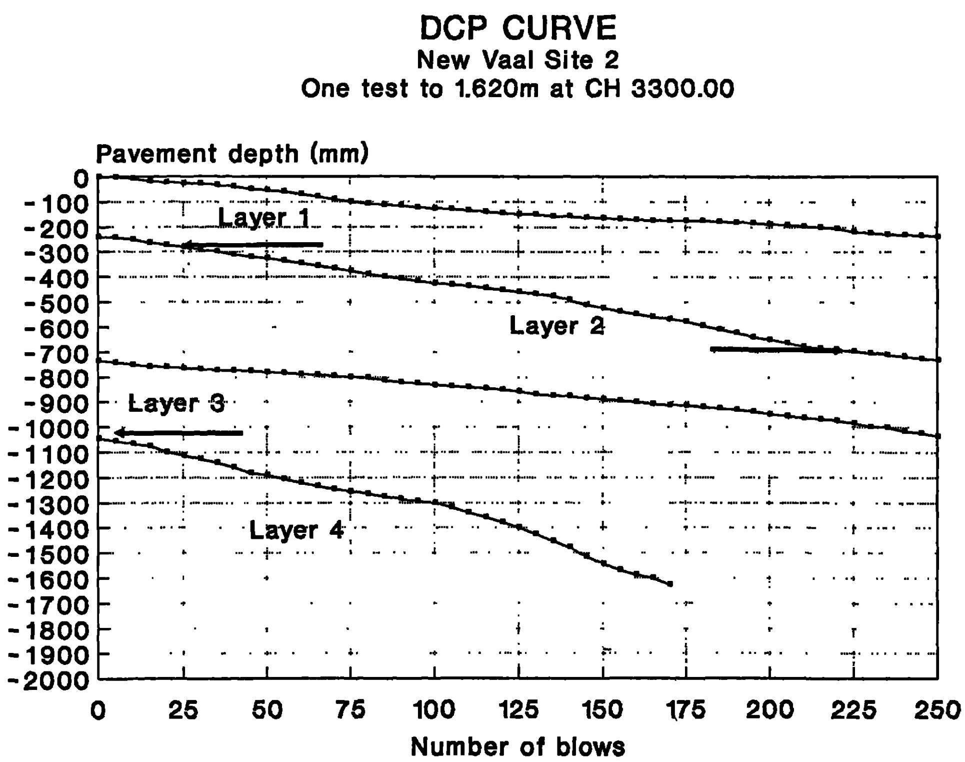

LAYER CBR DIAGRAM
SACE Kromdraai Site 3
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Redefined CBR from average layer strength values
CBR

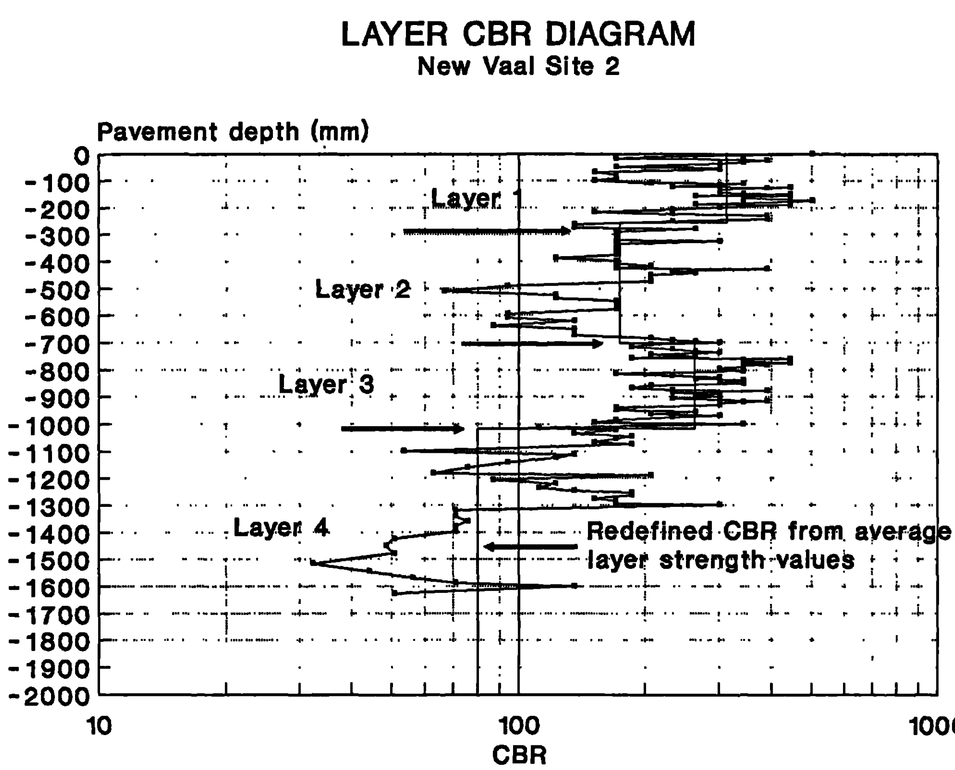

BALANCE CURVE
SACE Kromdraai Site 3
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
60
40
20
0
-20
-40
-60
0
10
20
30
40
50
60
70
80
90
100
% of pavement structure number

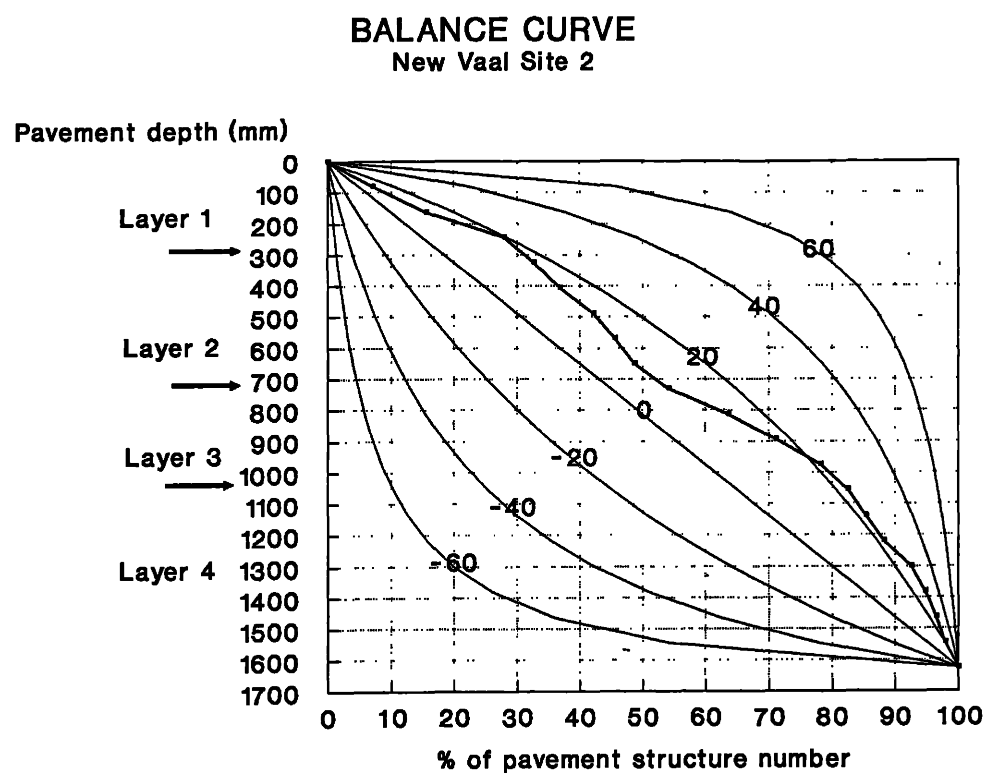

DCP CURVE
New Vaal Site 1
One test to 1.259m at CH 1200.00
Pavement depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
Layer 1
Layer 2
Layer 3
Layer 4
Refusal at 1259mm
0
25
50
75
100
125
150
175
200
225
250
Number of blows

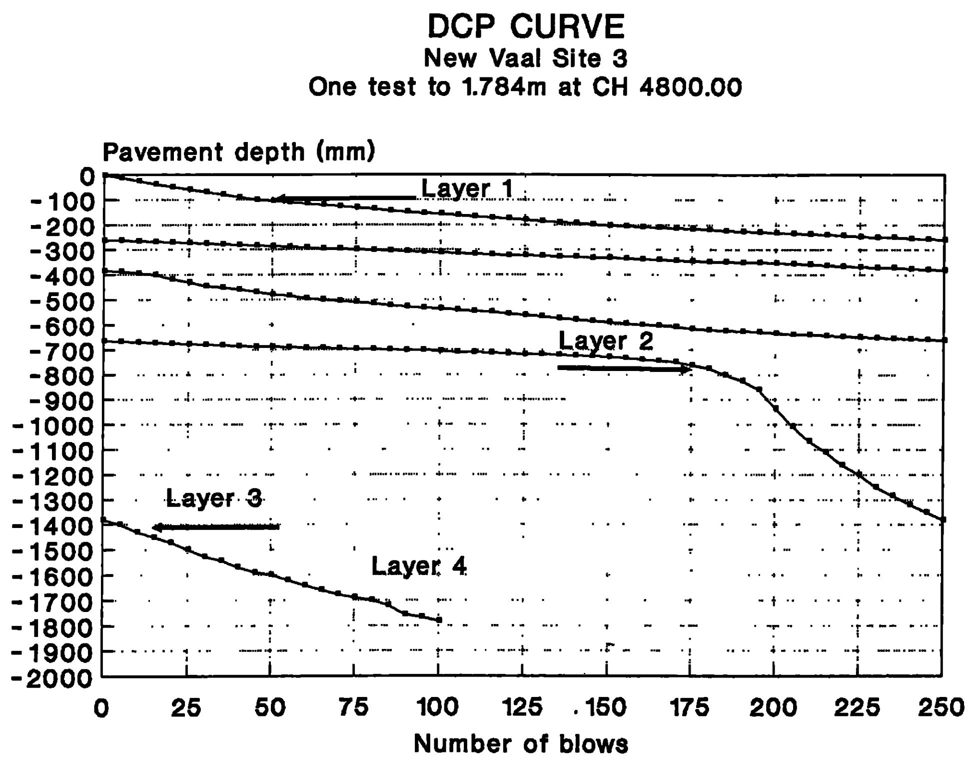

LAYER CBR DIAGRAM
New Vaal Site 1
Pavement depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
Layer 1
Layer 2
Layer 3
Layer 4
Redefined CBR from average layer strength values
Refusal at 1259mm
10
100
1000
CBR

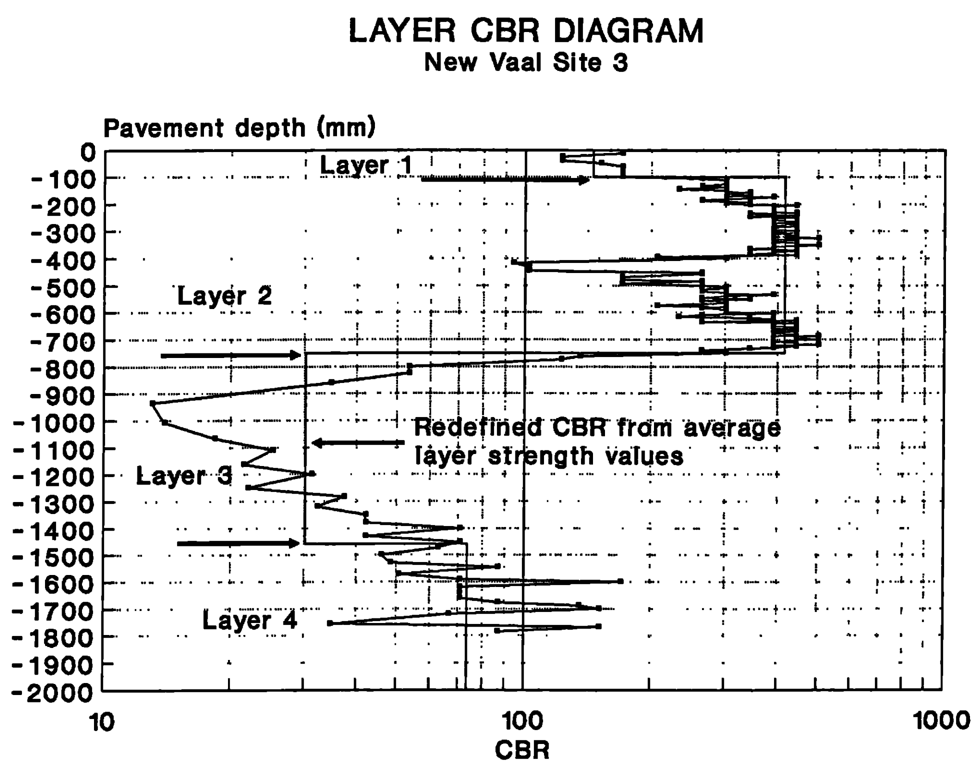

BALANCE CURVE
New Vaal Site 1
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
0
10
20
30
40
50
60
70
80
90
100
60
40
20
0
-20
-40
-60
% of pavement structure number

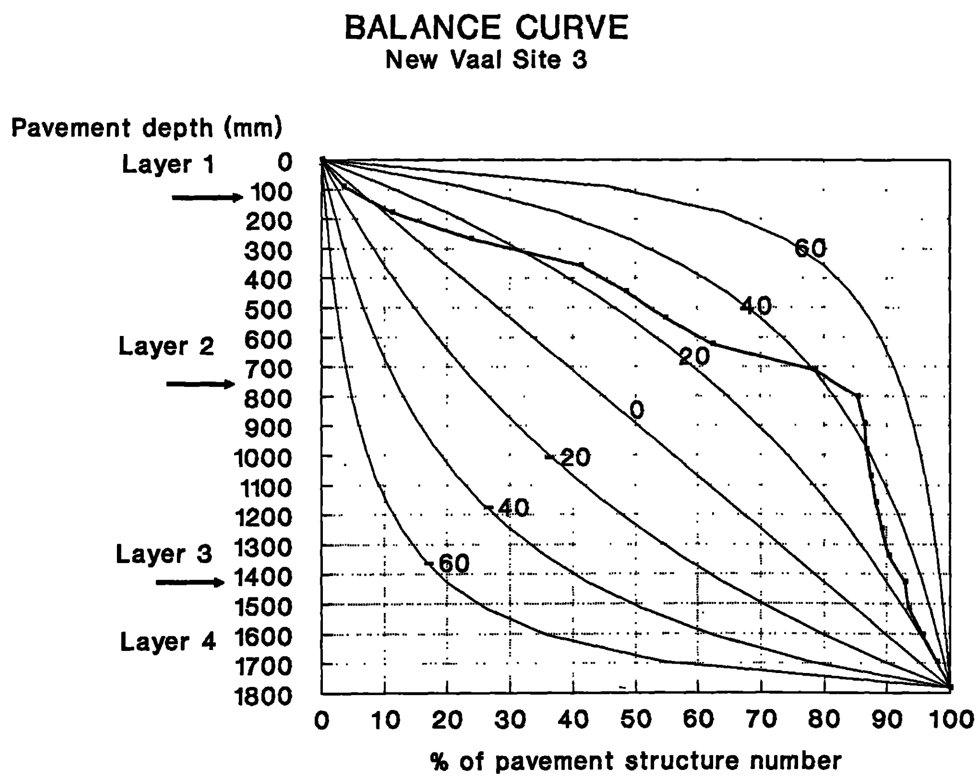

DCP CURVE
New Vaal Site 2
One test to 1.620m at CH 3300.00
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
Number of blows


LAYER CBR DIAGRAM
New Vaal Site 2
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
Redefined CBR from average layer strength values
CBR


BALANCE CURVE
New Vaal Site 2
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
60
40
20
0
-20
-40
-60
0 10 20 30 40 50 60 70 80 90 100
% of pavement structure number


DCP CURVE
New Vaal Site 3
One test to 1.784m at CH 4800.00
Pavement depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
-1600
-1700
-1800
-1900
-2000
Layer 1
Layer 2
Layer 3
Layer 4
0
25
50
75
100
125
150
175
200
225
250
Number of blows


LAYER CBR DIAGRAM
New Vaal Site 3
Pavement depth (mm)
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
-1300
-1400
-1500
-1600
-1700
-1800
-1900
-2000
Layer 1
Layer 2
Redefined CBR from average
layer strength values
Layer 3
Layer 4
10
100
1000
CBR


BALANCE CURVE
New Vaal Site 3
Pavement depth (mm)
Layer 1
Layer 2
Layer 3
Layer 4
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
60
40
20
0
-20
-40
-60
0 10 20 30 40 50 60 70 80 90 100
% of pavement structure number

APPENDIX C

CALIFORNIA BEARING RATIO (CBR) DESIGN PROCEDURE

Contents

CBR DESIGN METHOD Euclid R170 Kriel Colliery	REAR	FRONT
MAX LOAD PER WHEEL or DUAL SET (kN)	858.0	406.0
TYRE PRESSURE (kPa)	630.0	630.0
LOAD DISTRIBUTION (%)	55.0	45.0
LOAD REPETITION FACTOR (ALFA)	0.78	
CONTACT AREA SINGLE TYRE (SQ.M) (A)	1.362	0.644
CONTACT RADIUS SINGLE TYRE (M) (r)	0.658	0.453
		r EQUIV
TYRE WIDTH (M)	0.90	
FRONT TO REAR AXLE DISTANCE (m)	5.65	8.58
REAR DUAL ASSEMBLY WIDTH (m)	3.80	5.77
SINGLE DUAL CENTRE TO CENTRE DISTANCE (m)	1.37	

Table C1. Basic Data for CBR Cover Curve Evaluation.

	DEPTH (r)	A	B	C	D
FR	0.5	0.05	0.13	0.00	0.00
FL	0.5	0.15	0.13	0.00	0.00
BR	0.5	0.20	0.15	0.27	0.13
BL	0.5	0.11	0.15	0.27	1.34
	TOTAL	0.51	0.56	0.54	1.47

MAX DEFL	**1.47**
EQV DEFL	**1.34**
MAX ESWL(kN)	**941.24**

Table C2. ESWL for Points A B C and D at Depth 0.5r.

	DEPTH (r)	A	B	C	D
FR	1	0.06	0.13	0.00	0.00
FL	1	0.15	0.13	0.00	0.00
BR	1	0.21	0.15	0.28	0.13
BL	1	0.11	0.15	0.28	1.06
	TOTAL	0.53	0.56	0.56	1.19

MAX DEFL	**1.19**
EQV DEFL	**1.06**
MAX ESWL(kN)	**963.23**

Table C3. ESWL for Points A B C and D at Depth 1r.

	DEPTH (r)	A	B	C	D
FR	2	0.07	0.14	0.00	0.00
FL	2	0.16	0.14	0.00	0.00
BR	2	0.23	0.16	0.29	0.14
BL	2	0.12	0.16	0.29	0.67
	TOTAL	0.58	0.60	0.58	0.81

MAX DEFL	**0.81**
EQV DEFL	**0.67**
MAX ESWL(kN)	**1037.28**

Table C4. ESWL for Points A B C and D at Depth 2r.

	DEPTH (r)	A	B	C	D
FR	3	0.08	0.14	0.00	0.00
FL	3	0.17	0.14	0.00	0.00
BR	3	0.23	0.17	0.27	0.14
BL	3	0.12	0.17	0.27	0.47
	TOTAL	0.60	0.62	0.54	0.61

MAX DEFL	**0.62**
EQV DEFL	**0.47**
MAX ESWL(kN)	**1131.83**

Table C5. ESWL for Points A B C and D at Depth 3r.

	DEPTH (r)	A	B	C	D
FR	4	0.10	0.14	0.00	0.00
FL	4	0.16	0.14	0.00	0.00
BR	4	0.20	0.16	0.24	0.14
BL	4	0.11	0.16	0.24	0.36
	TOTAL	0.57	0.60	0.48	0.49

MAX DEFL	**0.60**
EQV DEFL	**0.36**
MAX ESWL(kN)	**1430.00**

Table C6. ESWL for Points A B C and D at Depth 4r.

	DEPTH (r)	A	B	C	D
FR	5	0.11	0.14	0.00	0.00
FL	5	0.15	0.14	0.00	0.00
BR	5	0.19	0.15	0.23	0.14
BL	5	0.11	0.15	0.23	0.29
	TOTAL	0.56	0.58	0.46	0.43

MAX DEFL	**0.58**
EQV DEFL	**0.29**
MAX ESWL(kN)	**1716.00**

Table C7. ESWL for Points A B C and D at Depth 5r.

Sample calculation for required CBR cover at specified depths

Following the modified Equation [4.12] which relates required pavement thickness *t* (inches) to CBR (%);

$$t = \alpha\sqrt{A}\left(-0.0481-1.1562\left(\log\frac{CBR}{p_e}\right)-0.6414\left(\log\frac{CBR}{p_e}\right)^2-0.4730\left(\log\frac{CBR}{p_e}\right)^3\right) \quad [4.12]$$

where

$$p_e = \frac{ESWL}{A} \quad [4.10]$$

and

ESWL	=	equivalent single wheel load (kN)
A	=	contact area (m^2)
α	=	repetition factor

using conversion factors of;

1 pound per square inch (psi)	=	6,894 kPa
1 inch	=	25,4mm

to accomodate the original units of Equation [4.12].

The repetition factor is calculated from the average annual run-of-mine tonnage produced by each mine and an average haul truck fully laden capacity of 154t, over a 20 year life of mine. In the case of Kriel Colliery, producing some 400 000tpa equates to approximately 52 000 total repetitions. If four wheels are considered when calculating the ESWL, the repetition factor equates to 0,78.

Pavement layer CBR values are calculated iteratively from Equation [4.12] such that the calculated and required depth points (*t*) agree to within 1%. Results are given in Table C8.

DEPTH (m)	Max ESWL (kN)	P_e (psi)	t (inches)	t (calculated from Eqn 4.12)	Corresponding CBR (%)
0.33	941.24	100.25	12.96	12.96	38.8
0.66	963.23	102.59	25.92	25.90	16.4
1.32	1037.28	110.48	51.84	51.50	5.6
1.98	1131.83	120.55	77.77	77.50	3.0
2.63	1430.00	152.51	103.69	102.44	2.3
3.29	1716.00	182.77	129.61	129.61	1.8

Table C8. Sample CBR Calculation Data at Various Depths of Pavement.

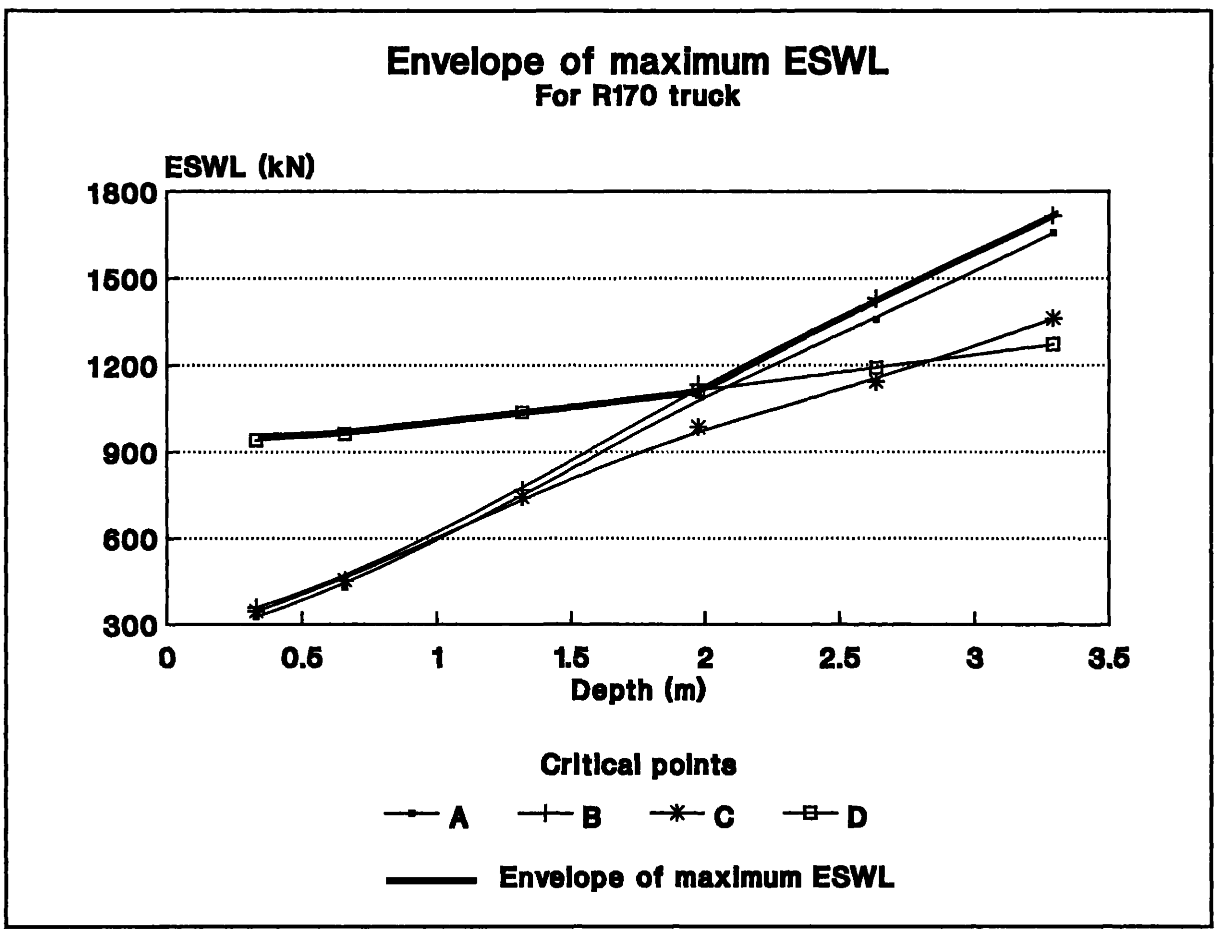


Figure C1 Envelope of maximum ESWL - R170 truck

CBR DESIGN METHOD Cat 772 (front and drive) Kriel Colliery		
	DRIVE	FRONT
MAX LOAD PER WHEEL or DUAL SET (kN)	322.0	113.0
TYRE PRESSURE (kPa)	630.0	630.0
LOAD DISTRIBUTION (%)	73.0	27.0
LOAD REPETITION FACTOR (ALFA)	0.78	
CONTACT AREA SINGLE TYRE (SQ.M) (A)	0.511	0.179
CONTACT RADIUS SINGLE TYRE (M) (r)	0.403	0.239
		r EQUIV
TYRE WIDTH (M)	0.60	
FRONT TO DRIVE AXLE DISTANCE (m)	3.88	9.62
DRIVE DUAL ASSEMBLY WIDTH (m)	2.60	6.45
SINGLE DUAL CENTRE TO CENTRE DISTANCE (m)	0.80	

Table C9. Basic Data for CBR Cover Curve Evaluation.

	DEPTH (r)	A	B	C	D		
FR	0.5	0.00	0.08	0.00	0.00	**MAX DEFL**	**1.46**
FL	0.5	0.11	0.08	0.00	0.00	**EQV DEFL**	**1.34**
BR	0.5	0.30	0.18	0.24	0.12	**MAX ESWL(kN)**	**350.84**
BL	0.5	0.11	0.18	0.24	1.34		
	TOTAL	0.52	0.52	0.48	1.46		

Table C10. ESWL for Points A B C and D at Depth 0.5r.

	DEPTH (r)	A	B	C	D		
FR	1	0.00	0.09	0.00	0.00	**MAX DEFL**	**1.18**
FL	1	0.11	0.09	0.00	0.00	**EQV DEFL**	**1.06**
BR	1	0.31	0.19	0.25	0.12	**MAX ESWL(kN)**	**358.45**
BL	1	0.12	0.19	0.25	1.06		
	TOTAL	0.54	0.56	0.50	1.18		

Table C11. ESWL for Points A B C and D at Depth 1r.

	DEPTH (r)	A	B	C	D		
FR	2	0.00	0.10	0.00	0.00	**MAX DEFL**	**0.79**
FL	2	0.12	0.10	0.00	0.00	**EQV DEFL**	**0.67**
BR	2	0.30	0.19	0.25	0.12	**MAX ESWL(kN)**	**379.67**
BL	2	0.12	0.19	0.25	0.67		
	TOTAL	0.54	0.58	0.50	0.79		

Table C12. ESWL for Points A B C and D at Depth 2r.

	DEPTH (r)	A	B	C	D		
FR	3	0.00	0.10	0.00	0.00	**MAX DEFL**	**0.59**
FL	3	0.12	0.10	0.00	0.00	**EQV DEFL**	**0.47**
BR	3	0.29	0.19	0.23	0.12	**MAX ESWL(kN)**	**404.21**
BL	3	0.12	0.19	0.23	0.47		
	TOTAL	0.53	0.58	0.46	0.59		

Table C13. ESWL for Points A B C and D at Depth 3r.

	DEPTH (r)	A	B	C	D
FR	4	0.00	0.11	0.00	0.00
FL	4	0.12	0.11	0.00	0.00
BR	4	0.25	0.18	0.22	0.12
BL	4	0.12	0.18	0.22	0.36
	TOTAL	0.49	0.58	0.44	0.48

MAX DEFL	**0.58**
EQV DEFL	**0.36**
MAX ESWL(kN)	**518.77**

Table C14. ESWL for Points A B C and D at Depth 4r.

	DEPTH (r)	A	B	C	D
FR	5	0.00	0.11	0.00	0.00
FL	5	0.12	0.11	0.00	0.00
BR	5	0.23	0.17	0.20	0.12
BL	5	0.12	0.17	0.20	0.29
	TOTAL	0.47	0.56	0.40	0.41

MAX DEFL	**0.56**
EQV DEFL	**0.29**
MAX ESWL(kN)	**621.79**

Table C15. ESWL for Points A B C and D at Depth 5r.

DEPTH (m)	**CBR(%)**
0.20	21.6
0.40	7.2
0.81	2.3
1.21	1.2
1.61	0.85
2.02	0.65

Table C16. CBR Data at Various Depths of Pavement.

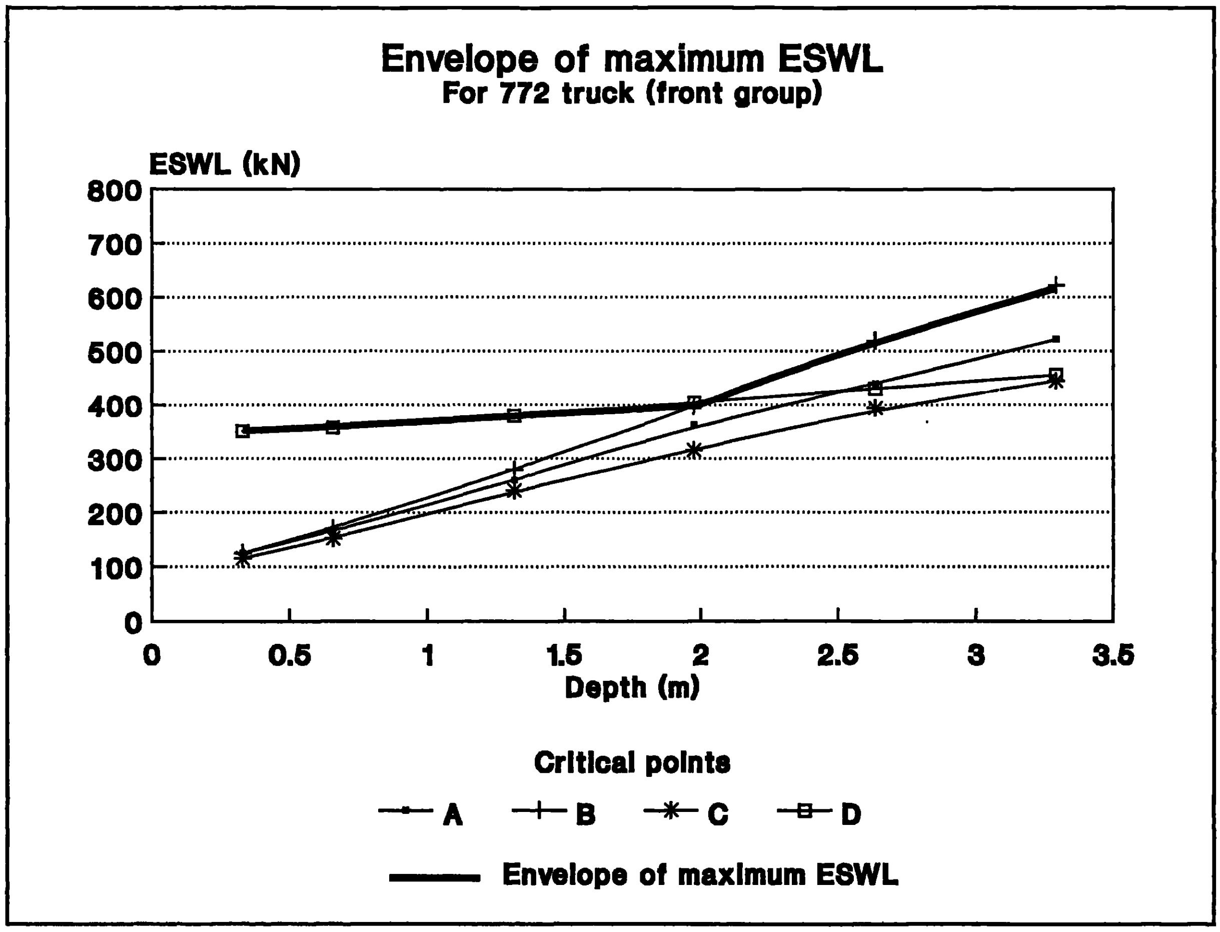


Figure C2 Envelope of maximum ESWL - 772 front group

CBR DESIGN METHOD Cat 772 (drive and rear) Kriel Colliery		
	REAR	DRIVE
MAX LOAD PER WHEEL or DUAL SET (kN)	402.0	322.0
TYRE PRESSURE (kPa)	630.0	630.0
LOAD DISTRIBUTION (%)	56.0	44.0
LOAD REPETITION FACTOR (ALFA)	1.000	
CONTACT AREA SINGLE TYRE (SQ.M) (A)	0.638	0.511
CONTACT RADIUS SINGLE TYRE (M) (r)	0.451	0.403
		r EQUIV
TYRE WIDTH (M)	0.60	
DRIVE TO REAR AXLE DISTANCE (m)	15.60	34.61
REAR DUAL ASSEMBLY WIDTH (m)	2.60	5.77
SINGLE DUAL CENTRE TO CENTRE DISTANCE (m)	0.80	

Table C17. Basic Data for CBR Cover Curve Evaluation.

	DEPTH (r)	A	B	C	D		
FR	0.5	0.00	0.00	0.00	0.00	**MAX DEFL**	**1.47**
FL	0.5	0.00	0.00	0.00	0.00	**EQV DEFL**	**1.34**
BR	0.5	0.00	0.00	0.25	0.13	**MAX ESWL(kN)**	**441.00**
BL	0.5	0.00	0.00	0.25	1.34		
	TOTAL	0.00	0.00	0.50	1.47		

Table C18. ESWL for Points A B C and D at Depth 0.5r.

	DEPTH (r)	A	B	C	D		
FR	1	0.00	0.00	0.00	0.00	**MAX DEFL**	**1.19**
FL	1	0.00	0.00	0.00	0.00	**EQV DEFL**	**1.06**
BR	1	0.00	0.00	0.26	0.13	**MAX ESWL(kN)**	**451.30**
BL	1	0.00	0.00	0.26	1.06		
	TOTAL	0.00	0.00	0.52	1.19		

Table C19. ESWL for Points A B C and D at Depth 1r.

	DEPTH (r)	A	B	C	D		
FR	2	0.00	0.00	0.00	0.00	**MAX DEFL**	**0.81**
FL	2	0.00	0.00	0.00	0.00	**EQV DEFL**	**0.67**
BR	2	0.00	0.00	0.27	0.14	**ESWL(kN)**	**486.00**
BL	2	0.00	0.00	0.27	0.67		
	TOTAL	0.00	0.00	0.54	0.81		

Table C20. ESWL for Points A B C and D at Depth 2r.

	DEPTH (r)	A	B	C	D		
FR	3	0.00	0.00	0.00	0.00	**MAX DEFL**	**0.61**
FL	3	0.00	0.00	0.00	0.00	**EQV DEFL**	**0.47**
BR	3	0.00	0.00	0.26	0.14	**MAX ESWL(kN)**	**521.74**
BL	3	0.00	0.00	0.26	0.47		
	TOTAL	0.00	0.00	0.52	0.61		

Table C21. ESWL for Points A B C and D at Depth 3r.

	DEPTH (r)	A	B	C	D		
FR	4	0.00	0.00	0.00	0.00	**MAX DEFL**	**0.50**
FL	4	0.00	0.00	0.00	0.00	**EQV DEFL**	**0.36**
BR	4	0.00	0.00	0.25	0.14	**MAX ESWL(kN)**	**558.33**
BL	4	0.00	0.00	0.25	0.36		
	TOTAL	0.00	0.00	0.50	0.50		

Table C22. ESWL for Points A B C and D at Depth 4r.

	DEPTH (r)	A	B	C	D		
FR	5	0.00	0.00	0.00	0.00	**MAX DEFL**	**0.46**
FL	5	0.00	0.00	0.00	0.00	**EQV DEFL**	**0.29**
BR	5	0.00	0.00	0.23	0.13	**MAX ESWL(kN)**	**637.65**
BL	5	0.00	0.00	0.23	0.29		
	TOTAL	0.00	0.00	0.46	0.42		

Table C23. ESWL for Points A B C and D at Depth 5 r.

DEPTH (m)	**CBR**
0.23	25.3
0.45	8.8
0.90	2.9
1.35	1.5
1.80	0.95
2.25	0.7

Table C24. CBR Data at Various Depths of Pavement.

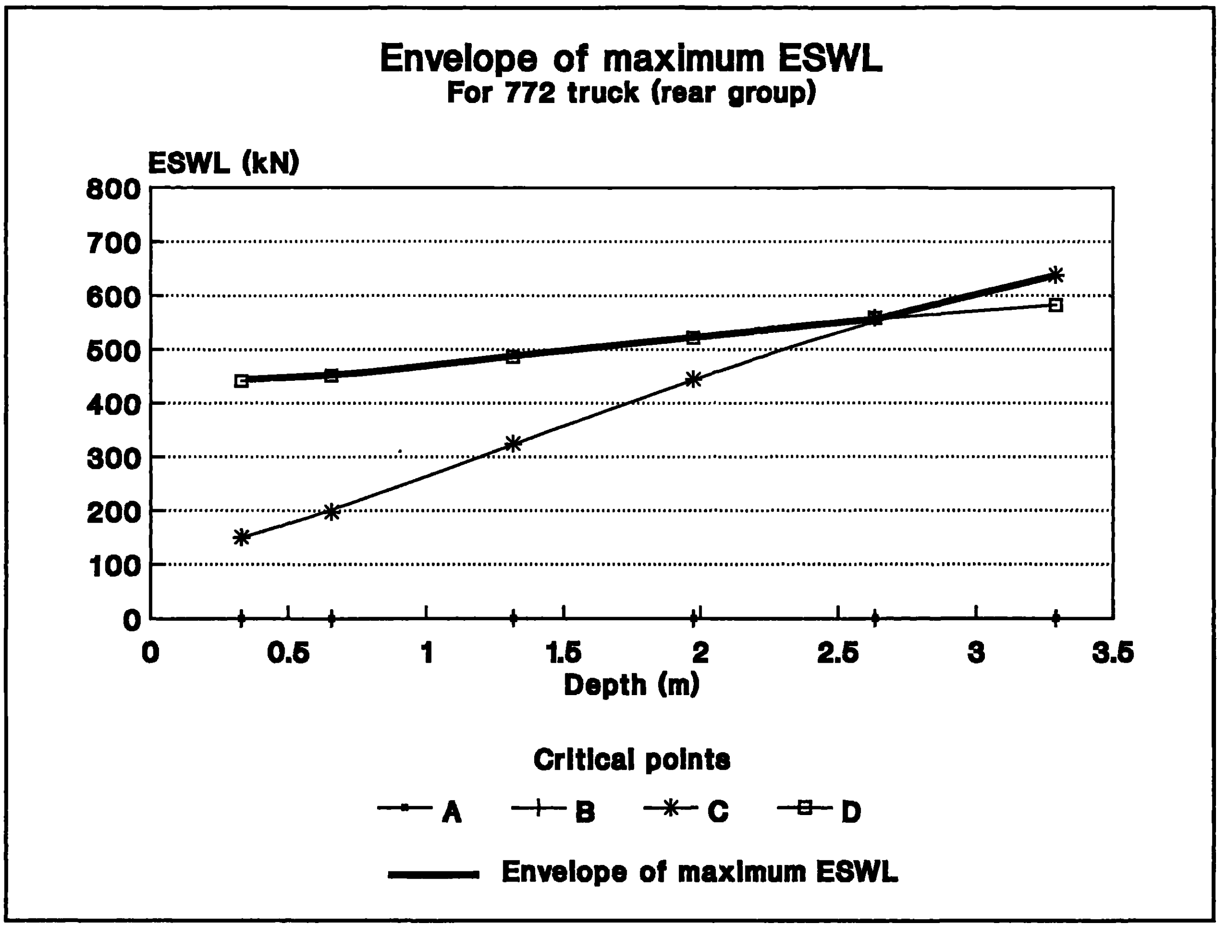


Figure C3 Envelope of maximum ESWL - 772 rear group

CBR DESIGN METHOD Haulpak 630E SACE Kromdraai Mine		
	REAR	FRONT
MAX LOAD PER WHEEL or DUAL SET (kN)	862.0	419.0
TYRE PRESSURE (kPa)	630.0	630.0
LOAD DISTRIBUTION (%)	67.0	33.0
LOAD REPETITION FACTOR (ALFA)	0.76	
CONTACT AREA SINGLE TYRE (SQ.M) (A)	1.368	0.665
CONTACT RADIUS SINGLE TYRE (M) (r)	0.660	0.460
		r EQUIV
TYRE WIDTH (M)	0.90	
FRONT TO REAR AXLE DISTANCE (m)	5.44	8.24
REAR DUAL ASSEMBLY WIDTH (m)	4.42	6.70
SINGLE DUAL CENTRE TO CENTRE DISTANCE (m)	1.44	

Table C25. Basic Data for CBR Cover Curve Evaluation.

	DEPTH (r)	A	B	C	D
FR	0.5	0.00	0.11	0.00	0.00
FL	0.5	0.13	0.11	0.00	0.00
BR	0.5	0.29	0.17	0.23	0.11
BL	0.5	0.10	0.17	0.23	1.34
	TOTAL	0.52	0.56	0.46	1.45

MAX DEFL	**1.45**
EQV DEFL	**1.34**
MAX ESWL(kN)	**932.76**

Table C26. ESWL for Points A B C and D at Depth 0.5r.

	DEPTH (r)	A	B	C	D
FR	1	0.00	0.11	0.00	0.00
FL	1	0.13	0.11	0.00	0.00
BR	1	0.30	0.18	0.24	0.11
BL	1	0.10	0.18	0.24	1.06
	TOTAL	0.53	0.58	0.48	1.17

MAX DEFL	**1.17**
EQV DEFL	**1.06**
MAX ESWL(kN)	**951.45**

Table C27. ESWL for Points A B C and D at Depth 1r.

	DEPTH (r)	A	B	C	D
FR	2	0.00	0.12	0.00	0.00
FL	2	0.14	0.12	0.00	0.00
BR	2	0.31	0.19	0.25	0.11
BL	2	0.11	0.19	0.25	0.67
	TOTAL	0.56	0.62	0.50	0.78

MAX DEFL	**0.78**
EQV DEFL	**0.67**
MAX ESWL(kN)	**1003.52**

Table C28. ESWL for Points A B C and D at Depth 2r.

	DEPTH (r)	A	B	C	D
FR	3	0.00	0.13	0.00	0.00
FL	3	0.15	0.13	0.00	0.00
BR	3	0.29	0.19	0.23	0.12
BL	3	0.12	0.19	0.23	0.47
	TOTAL	0.56	0.64	0.46	0.59

MAX DEFL	**0.64**
EQV DEFL	**0.47**
MAX ESWL(kN)	**1173.97**

Table C29. ESWL for Points A B C and D at Depth 3r.

	DEPTH (r)	A	B	C	D		
FR	4	0.00	0.13	0.00	0.00	**MAX DEFL**	**0.62**
FL	4	0.15	0.13	0.00	0.00	**EQV DEFL**	**0.36**
BR	4	0.25	0.18	0.20	0.12	**MAX ESWL(kN)**	**1484.56**
BL	4	0.12	0.18	0.20	0.36		
	TOTAL	0.52	0.62	0.40	0.48		

Table C30. ESWL for Points A B C and D at Depth 4r.

	DEPTH (r)	A	B	C	D		
FR	5	0.00	0.13	0.00	0.00	**MAX DEFL**	**0.58**
FL	5	0.14	0.13	0.00	0.00	**EQV DEFL**	**0.29**
BR	5	0.22	0.16	0.20	0.12	**MAX ESWL(kN)**	**1724.00**
BL	5	0.13	0.16	0.20	0.29		
	TOTAL	0.49	0.58	0.40	0.41		

Table C31. ESWL for Points A B C and D at Depth 5r.

DEPTH (r)	CBR(%)
0.33	38.5
0.66	16.1
1.32	5.4
1.98	3.1
2.64	2.35
3.30	1.8

Table C32. CBR Data at Various Depths of Pavement.

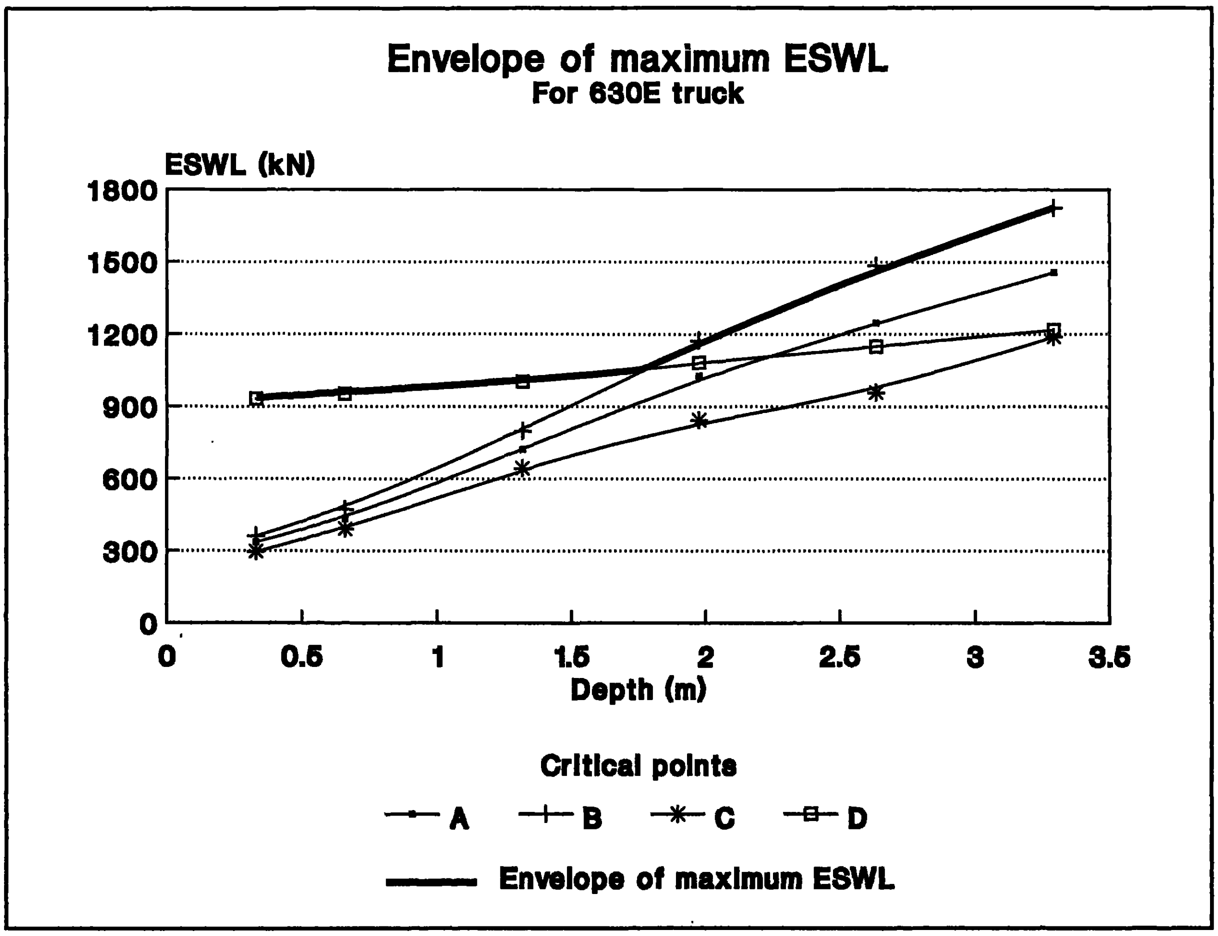


Figure C4 Envelope of maximum ESWL - 630E truck

CBR DESIGN METHOD Komatsu HD1600 M1 New Vaal Colliery		
	REAR	FRONT
MAX LOAD PER WHEEL or DUAL SET (kN)	878.0	401.0
TYRE PRESSURE (kPa)	630.0	630.0
LOAD DISTRIBUTION (%)	67.0	33.0
LOAD REPETITION FACTOR (ALFA)	1.000	
CONTACT AREA SINGLE TYRE (SQ.M) (A)	1.394	0.637
CONTACT RADIUS SINGLE TYRE (M) (r)	0.666	0.450
		r EQUIV
TYRE WIDTH (M)	0.90	
FRONT TO REAR AXLE DISTANCE (m)	6.00	9.01
REAR DUAL ASSEMBLY WIDTH (m)	4.38	6.58

Table C33. Basic Data for CBR Cover Curve Evaluation.

	DEPTH (r)	A	B	C	D
FR	0.5	0.00	0.11	0.00	0.00
FL	0.5	0.12	0.11	0.00	0.00
BR	0.5	0.25	0.16	0.24	0.12
BL	0.5	0.10	0.16	0.24	1.34
	TOTAL	0.47	0.54	0.48	1.46

MAX DEFL	**1.46**
EQV DEFL	**1.34**
MAX ESWL(kN)	**956.63**

Table C34. ESWL for Points A B C and D at Depth 0.5r.

	DEPTH (r)	A	B	C	D		
FR	1	0.00	0.11	0.00	0.00	**MAX DEFL**	**1.18**
FL	1	0.12	0.11	0.00	0.00	**EQV DEFL**	**1.06**
BR	1	0.25	0.16	0.24	0.12	**MAX ESWL(kN)**	**977.40**
BL	1	0.10	0.16	0.24	1.06		
	TOTAL	0.47	0.54	0.48	1.18		

Table C35. ESWL for Points A B C and D at Depth 1r.

	DEPTH (r)	A	B	C	D		
FR	2	0.00	0.12	0.00	0.00	**MAX DEFL**	**0.80**
FL	2	0.13	0.12	0.00	0.00	**EQV DEFL**	**0.67**
BR	2	0.26	0.17	0.25	0.13	**MAX ESWL(kN)**	**1048.36**
BL	2	0.11	0.17	0.25	0.67		
	TOTAL	0.50	0.58	0.50	0.80		

Table C36. ESWL for Points A B C and D at Depth 2r.

	DEPTH (r)	A	B	C	D		
FR	3	0.00	0.12	0.00	0.00	**MAX DEFL**	**0.60**
FL	3	0.14	0.12	0.00	0.00	**EQV DEFL**	**0.47**
BR	3	0.26	0.18	0.24	0.13	**MAX ESWL(kN)**	**1120.85**
BL	3	0.11	0.18	0.24	0.47		
	TOTAL	0.51	0.60	0.48	0.60		

Table C37. ESWL for Points A B C and D at Depth 3r.

	DEPTH (r)	A	B	C	D
FR	4	0.00	0.12	0.00	0.00
FL	4	0.14	0.12	0.00	0.00
BR	4	0.24	0.18	0.23	0.12
BL	4	0.11	0.18	0.23	0.36
	TOTAL	0.49	0.60	0.46	0.48

MAX DEFL	**0.60**
EQV DEFL	**0.36**
MAX ESWL(kN)	**1463.33**

Table C38. ESWL for Points A B C and D at Depth 4r.

	DEPTH (r)	A	B	C	D
FR	5	0.00	0.12	0.00	0.00
FL	5	0.14	0.12	0.00	0.00
BR	5	0.21	0.17	0.21	0.12
BL	5	0.11	0.17	0.21	0.29
	TOTAL	0.46	0.58	0.42	0.42

MAX DEFL	**0.58**
EQV DEFL	**0.29**
MAX ESWL(kN)	**1756.00**

Table C39. ESWL for Points A B C and D at Depth 5r.

DEPTH (r)	CBR(%)
0.33	39.0
0.67	16.5
1.33	5.6
2.00	2.9
2.66	2.3
3.33	1.8

Table C40. CBR Data at Various Depths of Pavement.

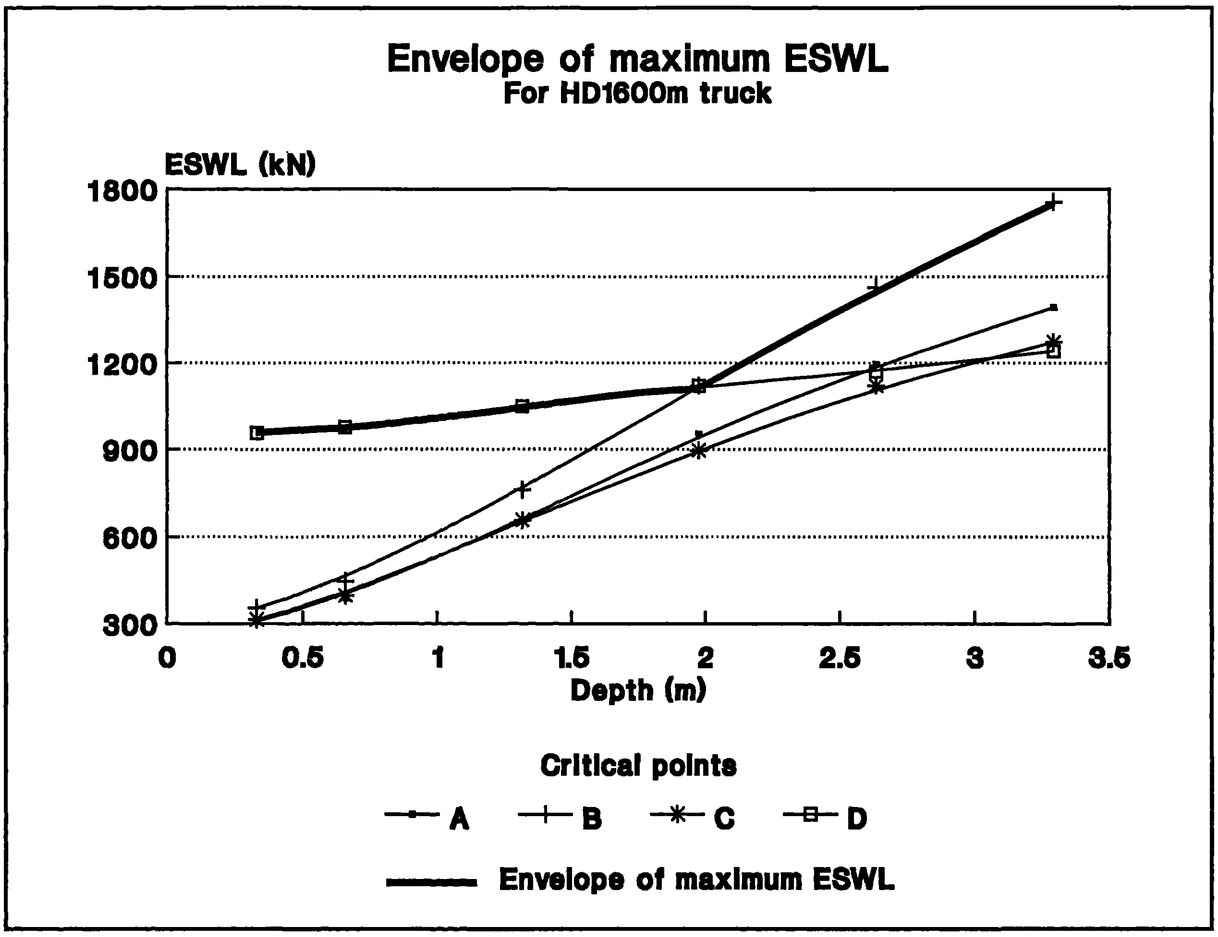
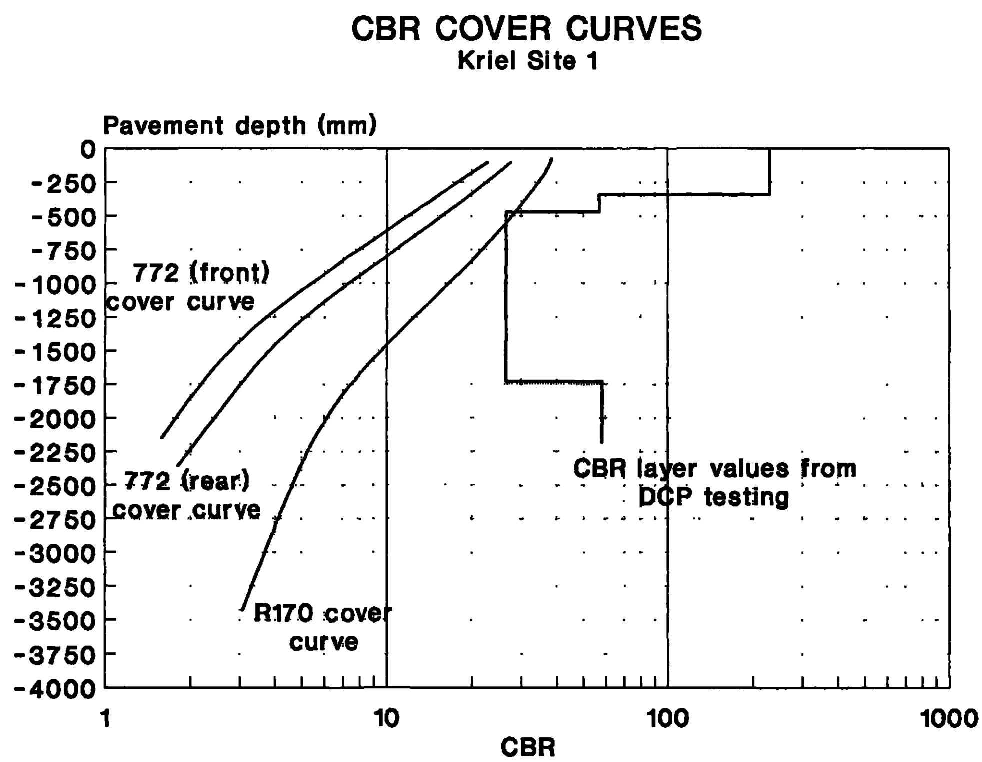
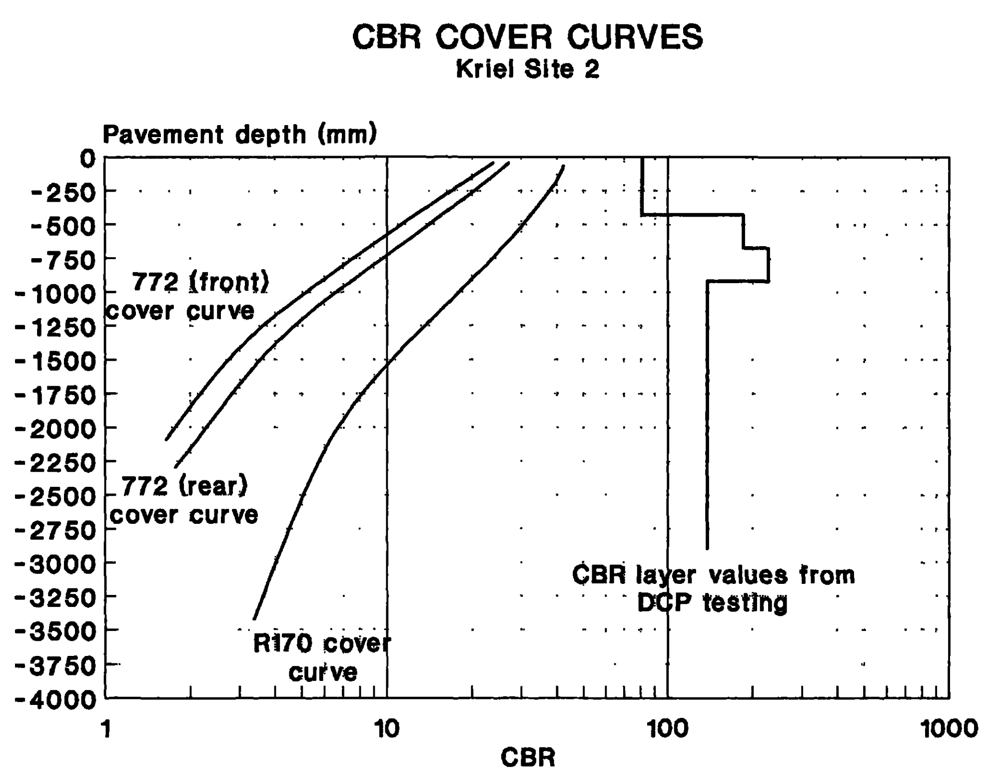
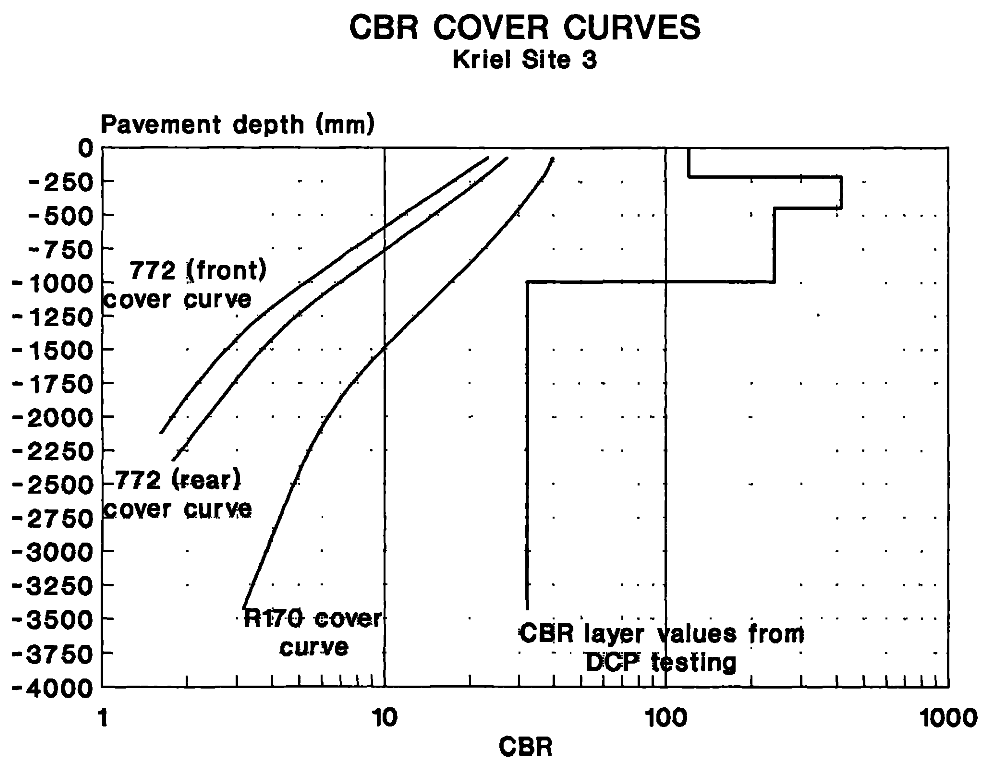


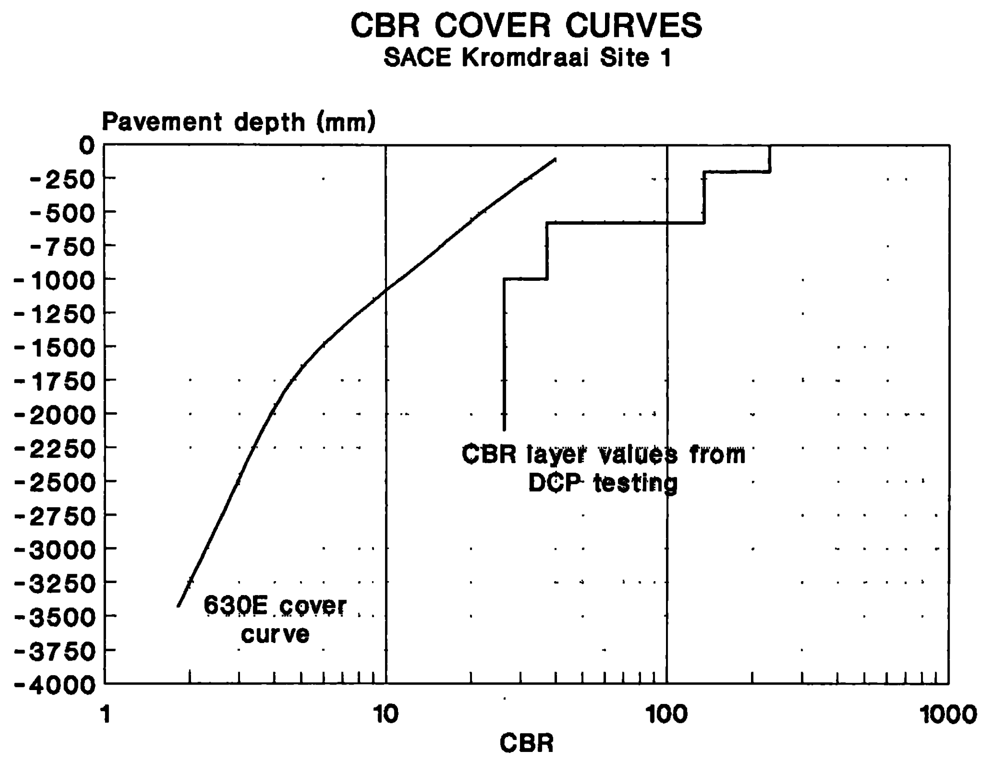
Figure C5 Envelope of maximum ESWL - HD1600 M1 truck

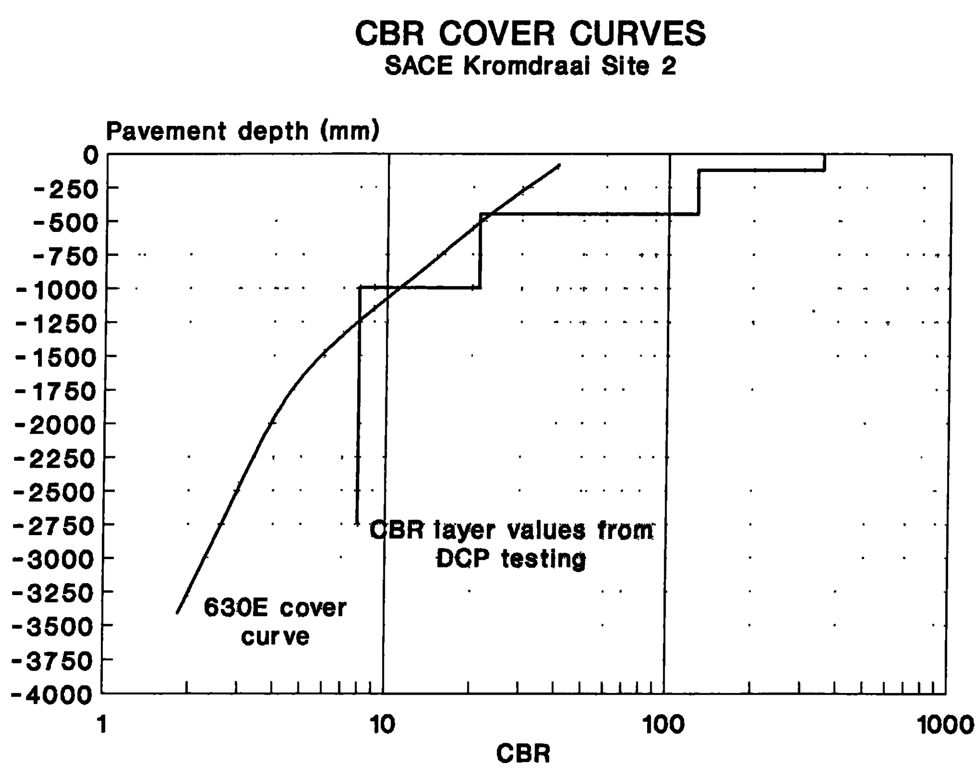

CBR COVER CURVES
Kriel Site 1
Pavement depth (mm)
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
-2750
-3000
-3250
-3500
-3750
-4000
772 (front) cover curve
772 (rear) cover curve
R170 cover curve
CBR layer values from DCP testing
1
10
100
1000
CBR

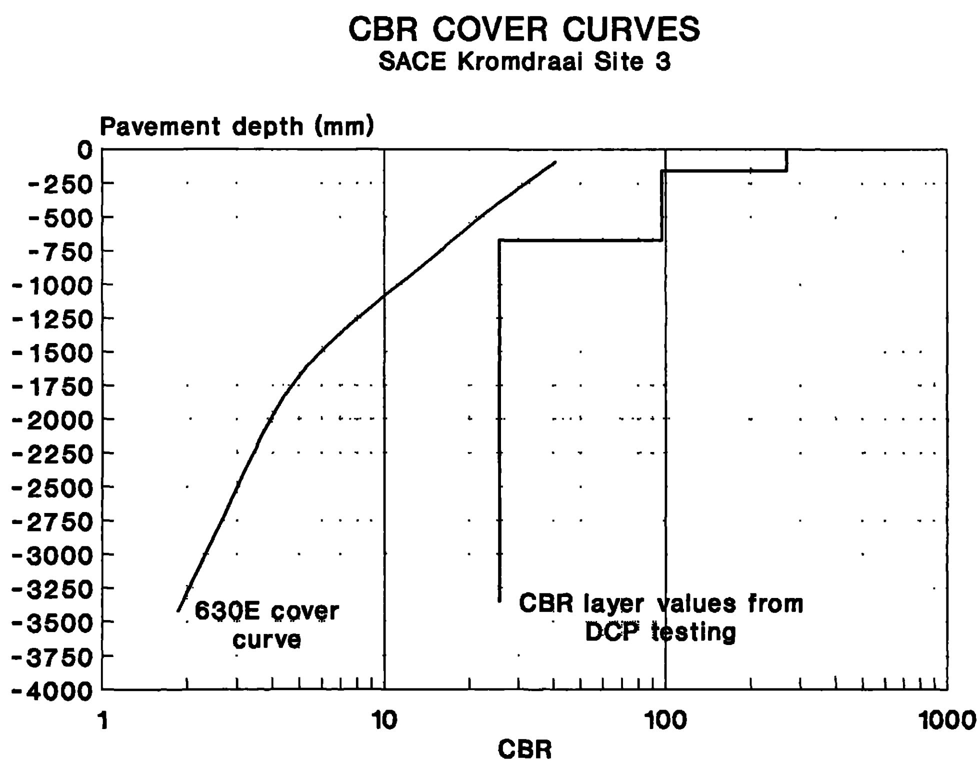

CBR COVER CURVES
Kriel Site 2
Pavement depth (mm)
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
-2750
-3000
-3250
-3500
-3750
-4000
772 (front) cover curve
772 (rear) cover curve
R170 cover curve
CBR layer values from DCP testing
1
10
100
1000
CBR

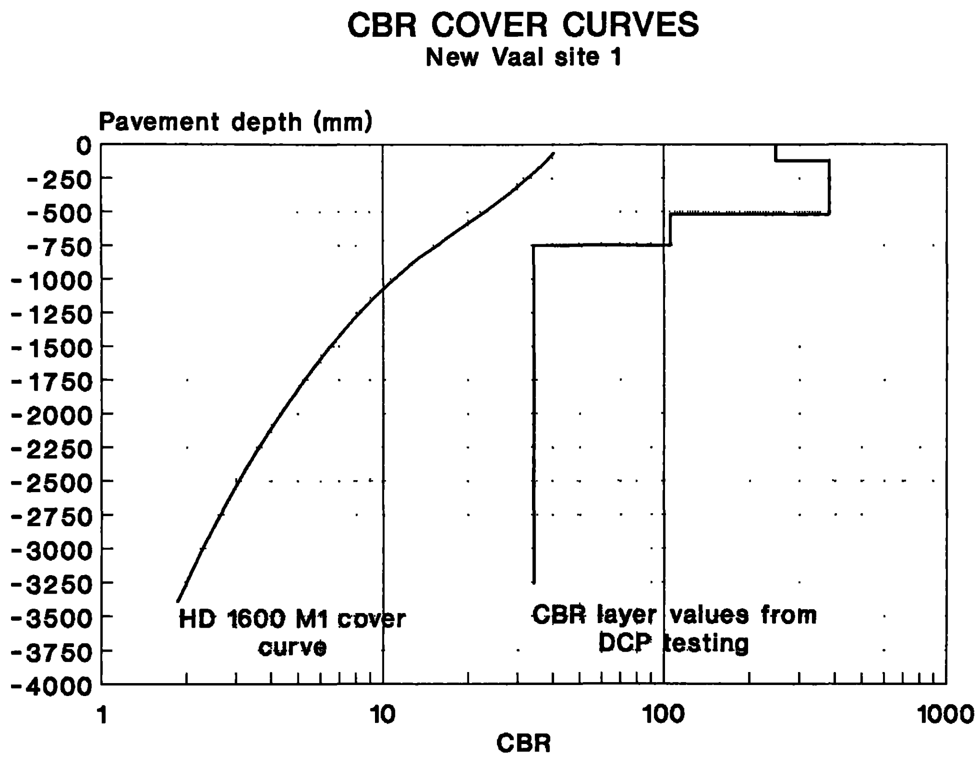


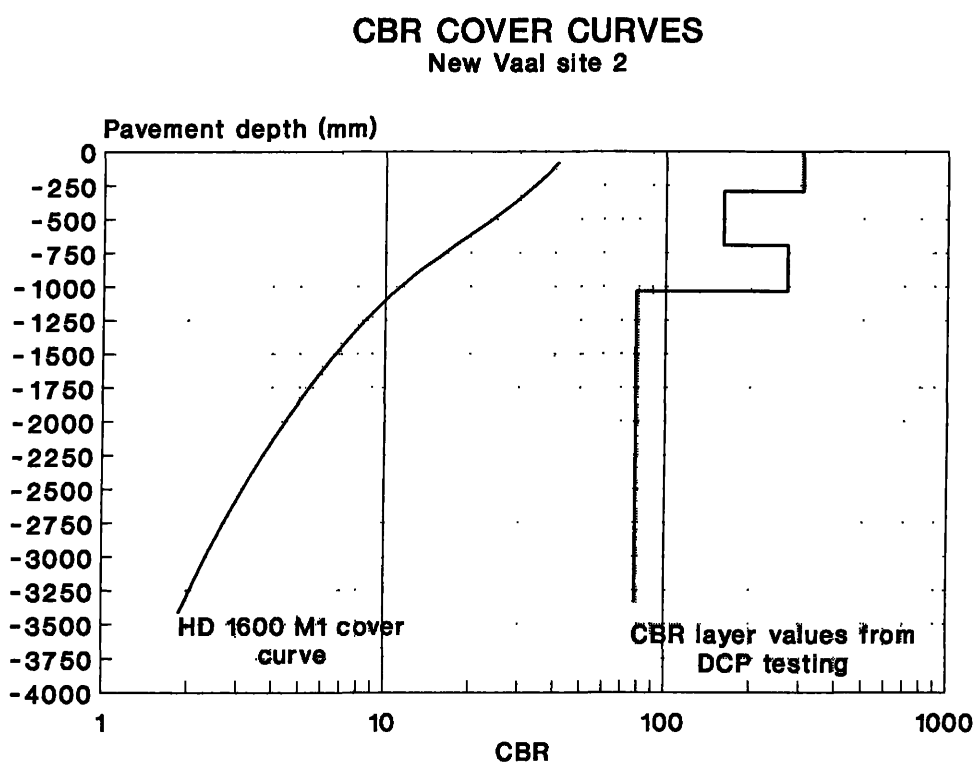
CBR COVER CURVES
Kriel Site 3
Pavement depth (mm)
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
-2750
-3000
-3250
-3500
-3750
-4000
772 (front) cover curve
772 (rear) cover curve
R170 cover curve
CBR layer values from DCP testing
1
10
100
1000
CBR

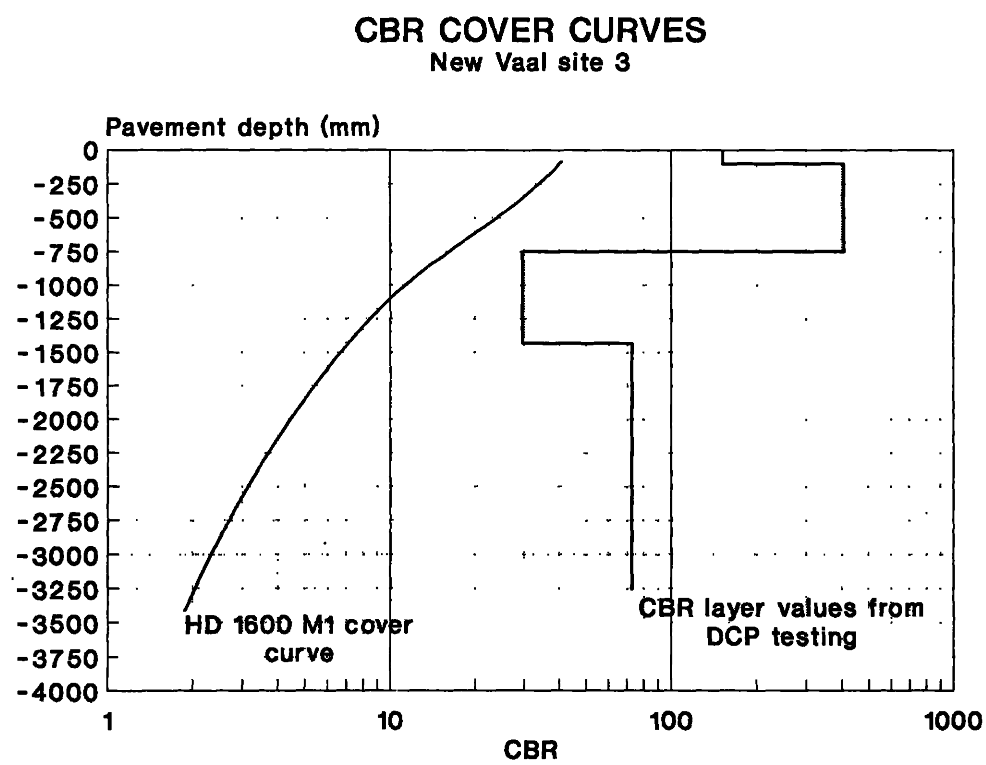

CBR COVER CURVES
SACE Kromdraai Site 1
Pavement depth (mm)
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
-2750
-3000
-3250
-3500
-3750
-4000
1
10
100
1000
CBR
CBR layer values from DCP testing
630E cover curve


CBR COVER CURVES
SACE Kromdraai Site 2
Pavement depth (mm)
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
-2750
-3000
-3250
-3500
-3750
-4000
1
10
100
1000
CBR
CBR layer values from DCP testing
630E cover curve


CBR COVER CURVES
SACE Kromdraai Site 3
Pavement depth (mm)
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
-2750
-3000
-3250
-3500
-3750
-4000
1
10
100
1000
CBR
630E cover curve
CBR layer values from DCP testing


CBR COVER CURVES
New Vaal site 1
Pavement depth (mm)
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
-2750
-3000
-3250
-3500
-3750
-4000
1
10
100
1000
CBR
HD 1600 M1 cover curve
CBR layer values from DCP testing


CBR COVER CURVES
New Vaal site 2
Pavement depth (mm)
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
-2750
-3000
-3250
-3500
-3750
-4000
1
10
100
1000
CBR
HD 1600 M1 cover curve
CBR layer values from DCP testing


CBR COVER CURVES
New Vaal site 3
Pavement depth (mm)
0
-250
-500
-750
-1000
-1250
-1500
-1750
-2000
-2250
-2500
-2750
-3000
-3250
-3500
-3750
-4000
1
10
100
1000
CBR
HD 1600 M1 cover curve
CBR layer values from DCP testing

APPENDIX D1

RESULTS OF MDD AND MECHANISTIC ANALYSIS - KRIEL COLLIERY

D1-2

Contents

UNIVERSITEIT VAN PRETORIA
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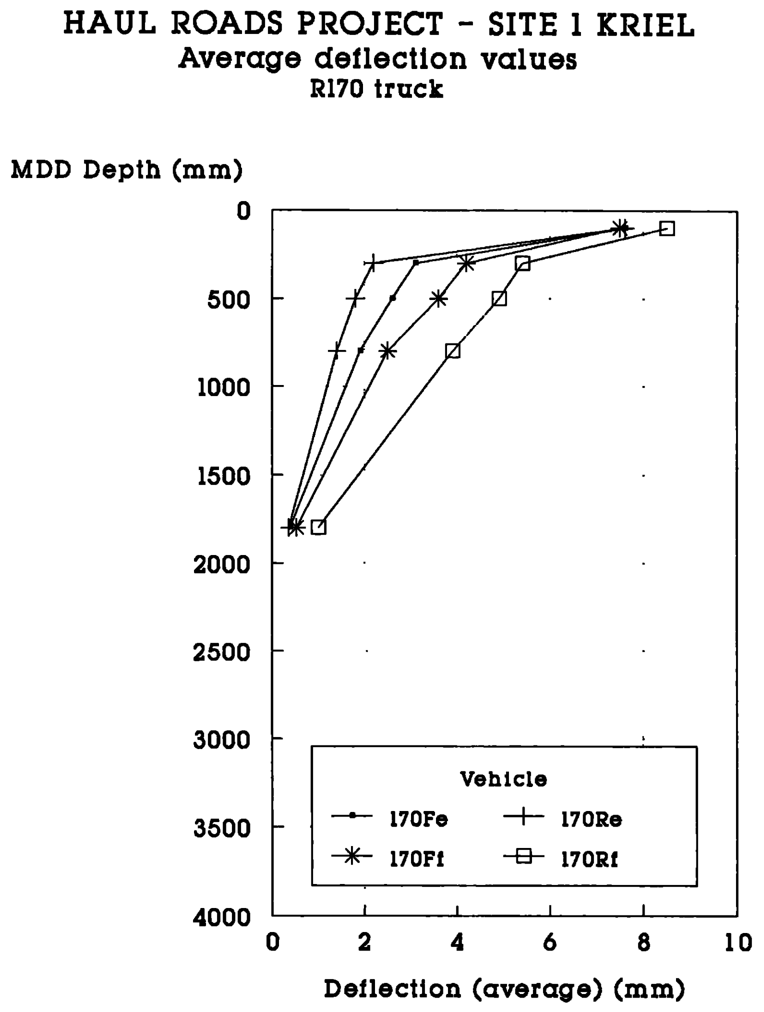
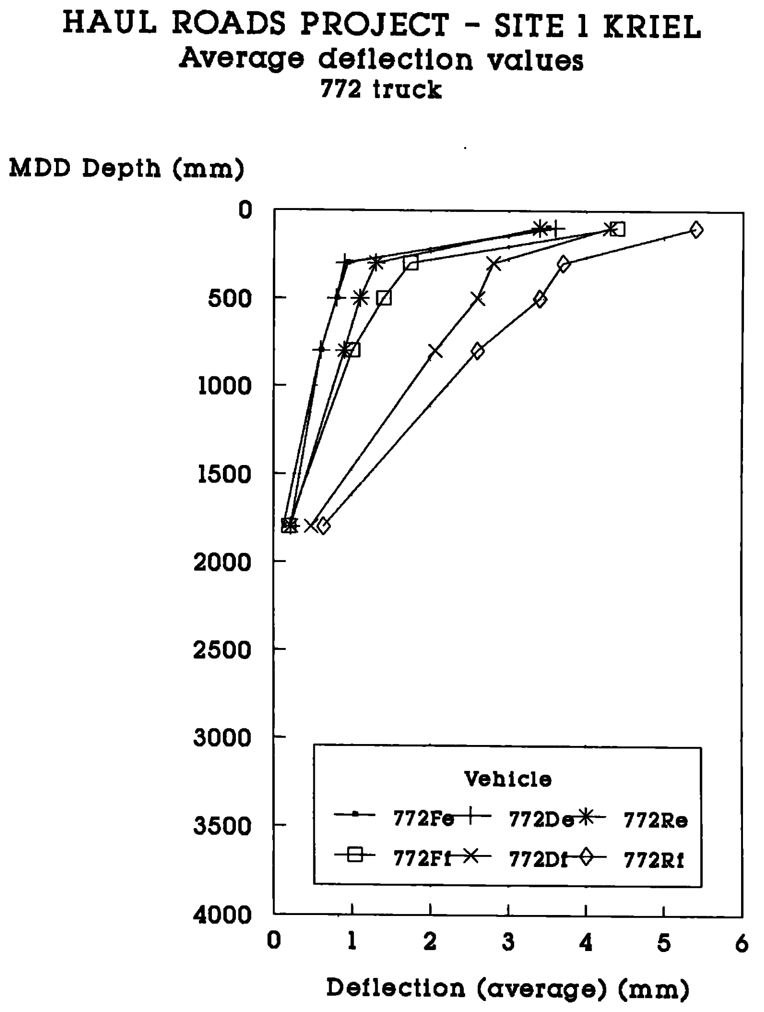
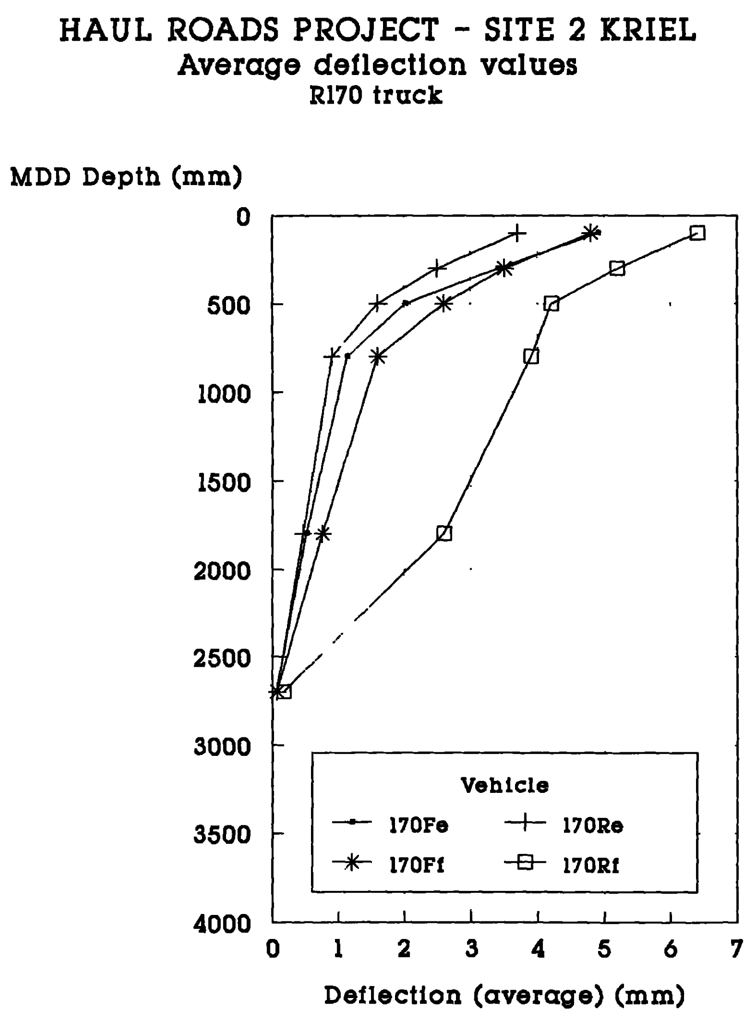
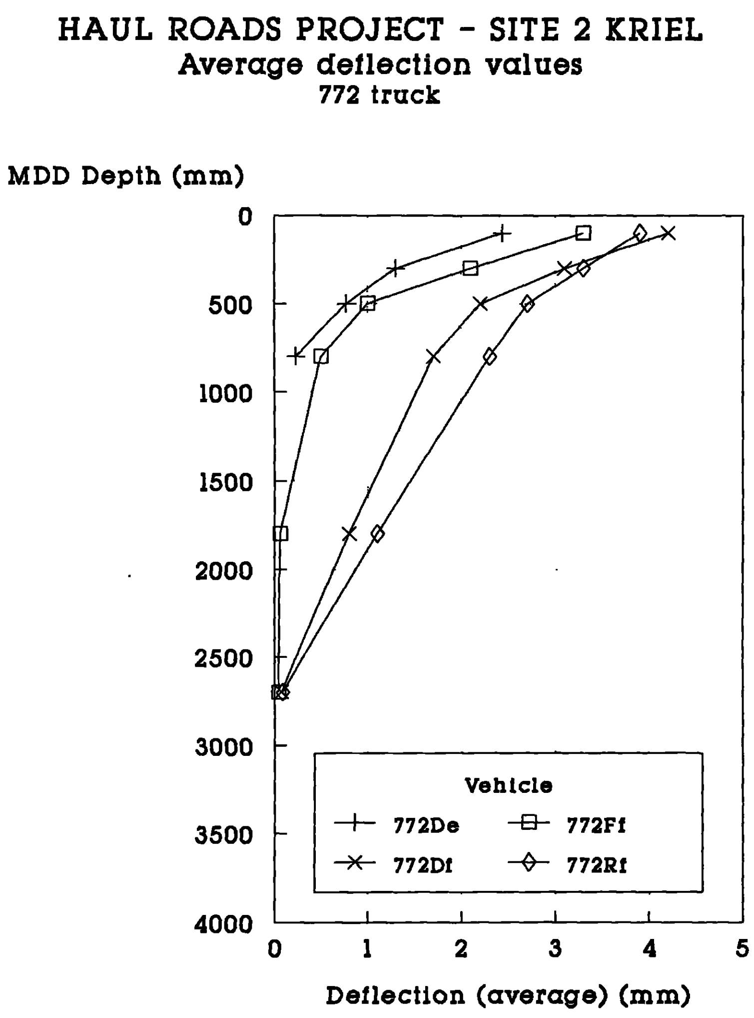
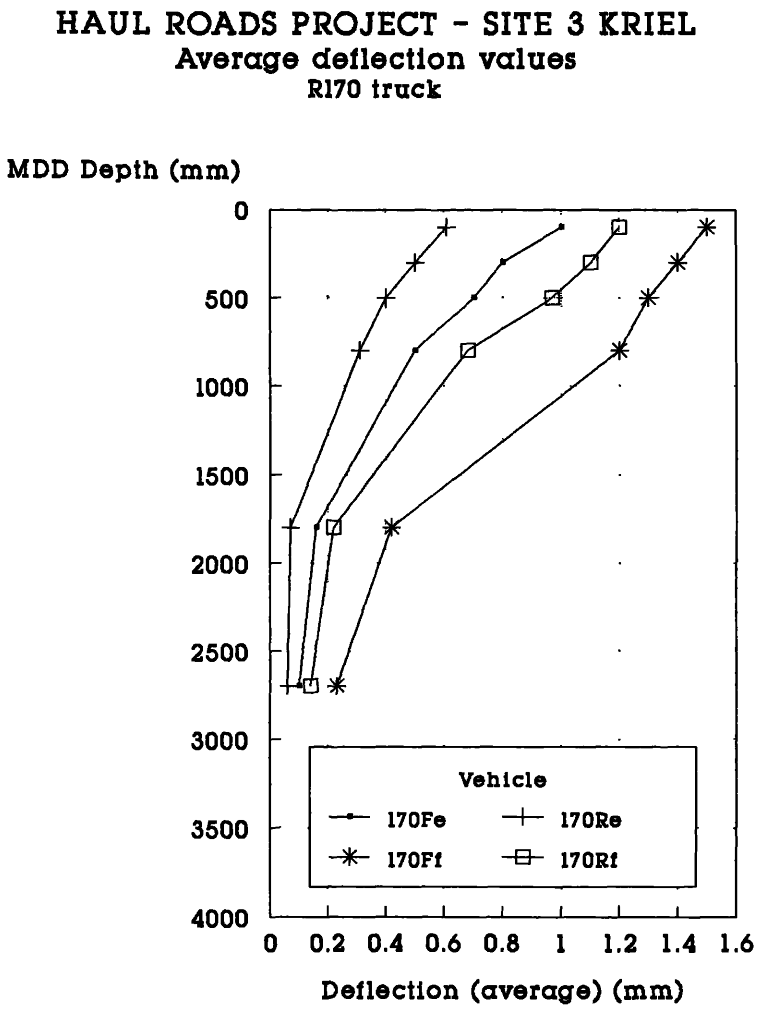
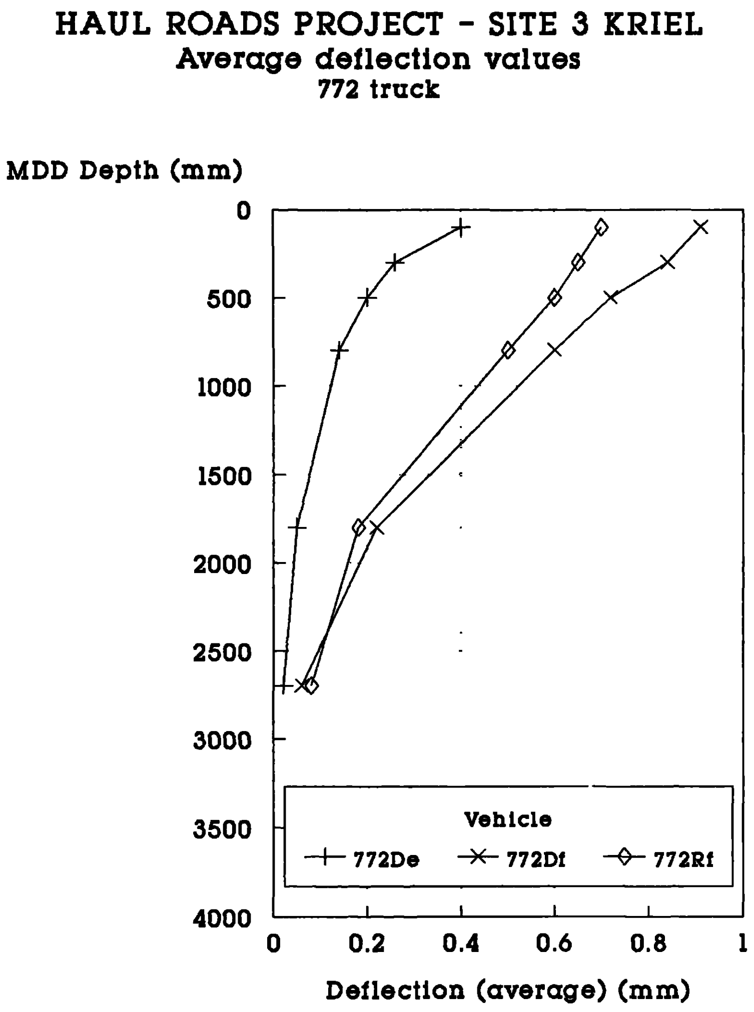





HAUL ROADS PROJECT - SITE 2 KRIEL
Average deflection values
R170 truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
1
2
3
4
5
6
7
Deflection (average) (mm)
Vehicle
170Fe
170Re
170Ff
170Rf


HAUL ROADS PROJECT - SITE 2 KRIEL
Average deflection values
772 truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
1
2
3
4
5
Deflection (average) (mm)
Vehicle
772De
772Ff
772Df
772Rf


HAUL ROADS PROJECT - SITE 3 KRIEL
Average deflection values
R170 truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Deflection (average) (mm)
Vehicle
170Fe
170Re
170Ff
170Rf


HAUL ROADS PROJECT - SITE 3 KRIEL
Average deflection values
772 truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.2
0.4
0.6
0.8
1
Deflection (average) (mm)
Vehicle
772De
772Df
772Rf

MINE	KRIEL COLLIERY
SITE NUMBER	1
TRUCK TYPE	R170
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	7.50	4.30	350	1249	180	
2	■300	4.20	4.10	300	-509	638	1512
3	■500 ■800	3.60 2.50	3.70 2.50	41	93	90	4917
4	■1800	0.53	0.53	21	89	41	2223

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MINE	KRIEL COLLIERY
SITE NUMBER	1
TRUCK TYPE	R170
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	7.60	3.40	200	1058	296	
2	■300	3.10	3.10	200	-98	444	1926
3	■500 ■800	2.60 1.90	2.60 1.70	50	65	74	4165
4	■1800	0.39	0.38	20	61	23	1615

MINE	KRIEL COLLIERY
SITE NUMBER	1
TRUCK TYPE	R170
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	8.50	5.70	350	1274	295	
2	■300	5.40	5.50	300	-472	698	1540
3	■500 ■800	4.90 3.90	4.90 3.60	40	145	125	5343
4	■1800	1.00	1.00	17	55	24	4288

MINE	KRIEL COLLIERY
SITE NUMBER	1
TRUCK TYPE	R170
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTION: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	7.60	2.30	380	928	310	
2	■300	2.20	2.20	380	-344	425	851
3	■500 ■800	1.80 1.40	1.90 1.40	41	52	47	2539
4	■1800	0.36	0.36	19	59	21	1476

MINE	KRIEL COLLIERY
SITE NUMBER	1
TRUCK TYPE	772
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	4.40	2.00	320	778	322	
2	■300	1.74	1.80	250	-279	305	1055
3	■500 ■800	1.40 1.00	1.50 1.00	28	25	26	2593
4	■1800	0.19	0.18	17	23	9	775

MINE	KRIEL COLLIERY
SITE NUMBER	1
TRUCK TYPE	772
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	3.50	1.11	550	707	321	
2	■300	0.94	0.97	450	-303	276	485
3	■500 ■800	0.80 0.60	0.80 0.60	35	18	17	1385
4	■1800	0.12	0.11	19	16	6	467

MINE	KRIEL COLLIERY
SITE NUMBER	1
TRUCK TYPE	772
WHEEL LOAD	DRIVE, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	4.30	2.90	450	989	283	
2	■300	2.80	2.90	400	-458	505	866
3	■500 ■800	2.60 2.06	2.70 2.00	36	63	58	2918
4	■1800	0.47	0.48	16	64	23	1975

MINE	KRIEL COLLIERY
SITE NUMBER	1
TRUCK TYPE	772
WHEEL LOAD	DRIVE, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	3.60	1.00	550	618	329	
2	■300	0.90	0.90	500	-136	177	398
3	■500 ■800	0.80 0.60	0.85 0.65	55	22	25	975
4	■1800	0.21	0.20	14	25	8	818

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MINE	KRIEL COLLIERY
SITE NUMBER	1
TRUCK TYPE	772
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTION: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	5.40	3.70	450	1694	257	
2	■300	3.70	3.70	400	-555	597	969
3	■500 ■800	3.40 2.60	3.40 2.54	35	72	67	3529
4	■1800	0.63	0.63	15	75	27	2579

MINE	KRIEL COLLIERY
SITE NUMBER	1
TRUCK TYPE	772
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	3.40	1.30	550	625	313	
2	■300	1.30	1.30	500	-260	223	406
3	■500 ■800	1.10 0.90	1.20 0.92	25	24	19	1360
4	■1800	0.21	0.20	14	24	8	830

MINE	KRIEL COLLIERY
SITE NUMBER	2
TRUCK TYPE	R170
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300	4.8 3.5	4.00 3.55	200	876	369	
2	■500	2.6	2.60	42	569	227	7443
3	■800	1.6	1.60	5000	-128	300	-144
4	■1800 ■2700	0.76 0.066	1.76 0.056	33	50	29	1297

MINE	KRIEL COLLIERY
SITE NUMBER	2
TRUCK TYPE	R170
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300	4.90 3.40	4.30 3.40	100	781	400	
2	■500	2.02	2.20	35	444	215	8368
3	■800	1.14	1.30	3000	-59	218	-110
4	■1800 ■2700	0.51 0.05	0.50 0.05	36	36	24	1077

MINE	KRIEL COLLIERY
SITE NUMBER	2
TRUCK TYPE	R170
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300	6.40 5.20	5.70 5.30	200	1051	309	
2	■500	4.20	4.60	60	604	237	5505
3	■800	3.90	4.30	3000	-387	465	-233
4	■1800 ■2700	2.60 0.16	1.20 0.15	20	85	44	2754

MINE	KRIEL COLLIERY
SITE NUMBER	2
TRUCK TYPE	R170
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300	3.70 2.50	3.10 2.60	120	622	386	
2	■500	1.60	1.59	30	296	119	6606
3	■800	0.90	0.90	3700	-26	156	-74
4	■1800 ■2700	0.46 0.06	0.43 0.03	50	38	26	664

MINE	KRIEL COLLIERY
SITE NUMBER	2
TRUCK TYPE	772
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300	3.30 2.10	3.90 2.10	45	593	405	
2	■500	1.00	1.00	50	263	165	4874
3	■800	0.50	0.57	5000	-46	123	-47
4	■1800 ■2700	0.05 0.04	0.20 0.02	25	12	7	456

MINE	KRIEL COLLIERY
SITE NUMBER	2
TRUCK TYPE	772
WHEEL LOAD	DRIVE, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300	4.20 3.10	4.40 3.10	55	728	410	
2	■500	2.20	2.15	50	381	155	5466
3	■800	1.70	1.70	4500	-117	232	-134
4	■1800 ■2700	0.80 0.07	0.80 0.06	25	38	22	1206

MINE	KRIEL COLLIERY
SITE NUMBER	2
TRUCK TYPE	772
WHEEL LOAD	DRIVE, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300	2.44 1.30	2.60 1.30	55	445	345	
2	■500	0.77	0.77	80	161	100	2075
3	■800	0.23	0.30	5000	-60	102	-50
4	■1800 ■2700			25 (average)	15	8.5	463

MINE	KRIEL COLLIERY
SITE NUMBER	2
TRUCK TYPE	772
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300	3.90 3.30	3.30 3.20	160	809	371	
2	■500	2.70	2.76	58	438	169	4355
3	■800	2.30	2.35	4200	-229	301	-165
4	■1800 ■2700	1.10 0.08	1.10 0.80	18	39	22	1620

MINE	KRIEL COLLIERY
SITE NUMBER	3
TRUCK TYPE	R170
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.50	1.50	500	1627	94	
2	■300	1.40	1.40	2500	-13	520	-370 (horizontal)
3	■500 ■800	1.30 1.20	1.30 1.00	140	154	131	1320
4	■1800 ■2700	0.42 0.23	0.43 0.19	125	30	29	767

MINE	KRIEL COLLIERY
SITE NUMBER	3
TRUCK TYPE	R170
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.00	1.00	200	1294	296	
2	■300	0.80	0.78	2500	161	437	-290 (horizontal)
3	■500 ■800	0.70 0.50	0.71 0.46	160	162	115	1058
4	■1800 ■2700	0.16 0.10	0.16 0.07	250	22	22	343

MINE	KRIEL COLLIERY
SITE NUMBER	3
TRUCK TYPE	R170
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.20	1.20	600	1545	156	
2	■300	1.10	1.10	2500	-369	687	-353 (horizontal)
3	■500 ■800	0.97 0.68	0.99 0.69	160	305	163	1315
4	■1800 ■2700	0.22 0.84	0.29 0.01	450	69	63	351

MINE	KRIEL COLLIERY
SITE NUMBER	3
TRUCK TYPE	772
WHEEL LOAD	DRIVE, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	0.40	0.40	300	908	428	
2	■300	0.26	0.22	2400	124	242	-113 (horizontal)
3	■500 ■800	0.20 0.14	0.20 0.14	230	72	48	324
4	■1800 ■2700	0.05 0.02	0.05 0.02	400	11	11	96

MINE	KRIEL COLLIERY
SITE NUMBER	3
TRUCK TYPE	772
WHEEL LOAD	DRIVE, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	0.91	0.92	250	1226	345	
2	■300	0.84	0.76	2600	82	263	-290 (horizontal)
3	■500 ■800	0.72 0.60	0.71 0.46	130	171	97	952
4	■1800 ■2700	0.22 0.06	0.17 0.07	300	28	27	238

MINE	KRIEL COLLIERY
SITE NUMBER	3
TRUCK TYPE	772
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	0.70	0.70	600	1351	274	
2	■300	0.65	0.66	2900	87	342	-240 (horizontal)
3	■500 ■800	0.60 0.50	0.62 0.45	263	182	124	694
4	■1800 ■2700	0.18 0.08	0.18 0.08	320	32	31	312

SAFETY FACTOR ESTIMATION - KRIEL COLLIERY

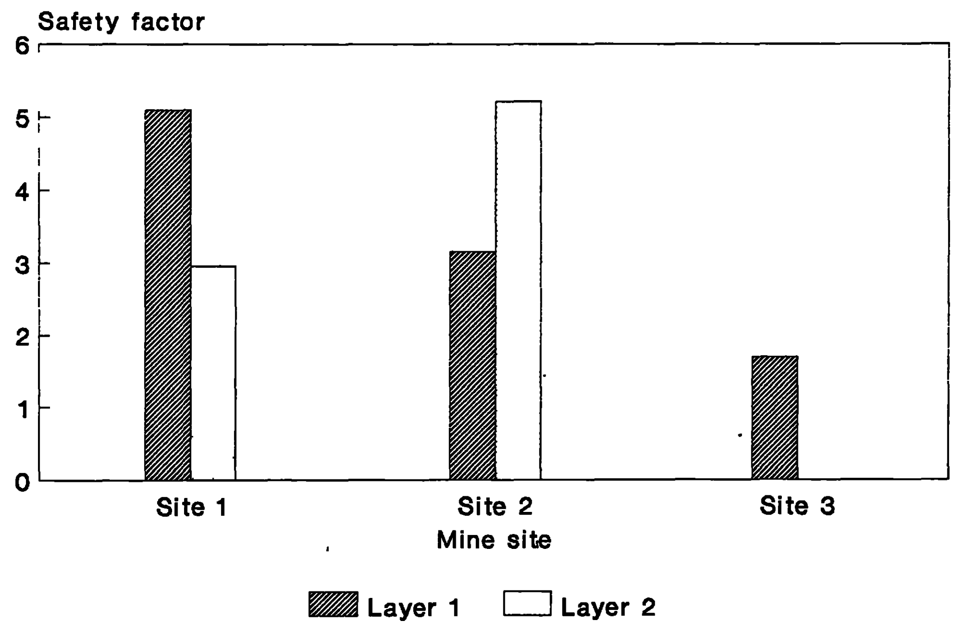
C-TERM = 223
Phi-TERM = 5.5

Minor principle stress (kPa)		Site 1		Site 2		Site 3	
		layer 1	layer 2	layer 1	layer 2	layer 1	layer 2
R170	FF	435	80	335	200	559	
	FE	402	41	327	184	487	
	RF	463	74	144	119	255	
	RE	364	-37	218	55	53	
Cat 772	FF	313	-42	266	116	424	
	FE	290	-55				
	DF	252	-95	314	162	178	
	DE	262	-3	207	70	375	
	RF	348	-189	335	182	500	
	RE	263	-35			370	
Deviator stress (kPa)							
R170	FF	254	511	348	198	94	
	FE	296	444	400	215	279	
	RF	195	689	323	84	80	
	RE	310	425	343	38	303	
Cat 772	FF	322	305	405	165	393	
	FE	321	27				
	DF	220	558	410	155	345	
	DE	329	177	345	62	428	
	RF	257	789	371	169	274	
	RE	313	223			367	

D1-31

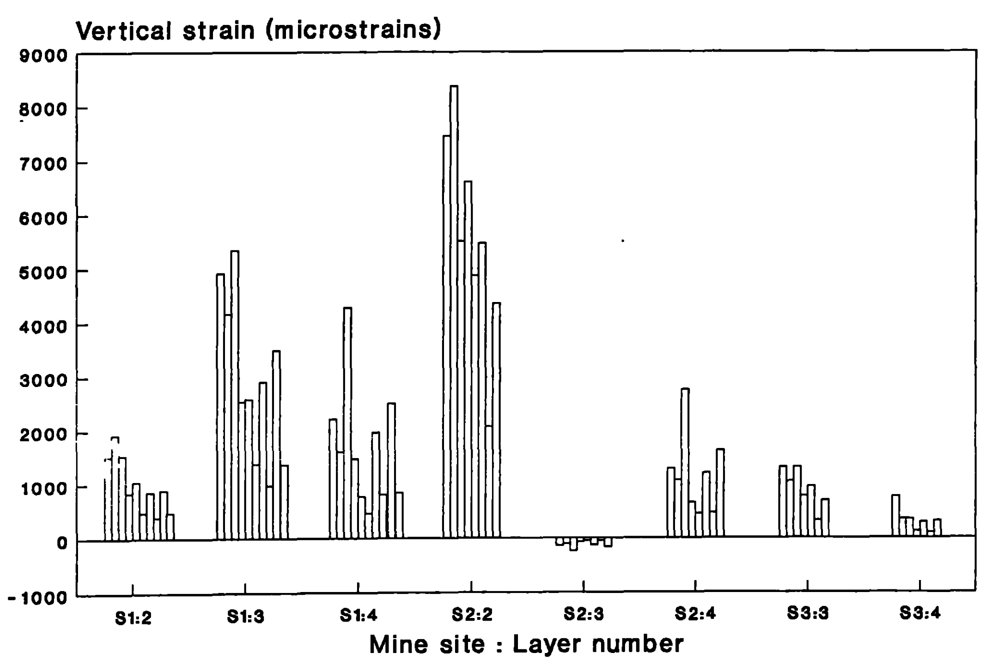
Safety factor							
R170	FF	10.30	1.30	5.94	6.68	35.08	
	FE	8.22	1.01	5.05	5.74	10.40	
	RF	14.20	0.91	3.14	10.45	20.32	
	RE	7.18	0.05	4.15	13.83	1.70	
Cat 772	FF	6.04	-0.03	4.16	5.22	6.50	
	FE	5.66	-2.94				
	DF	7.31	-0.54	4.76	7.19	3.48	
	DE	5.06	1.17	3.95	9.21	5.34	
	RF	8.32	-1.03	5.57	7.14	10.85	
	RE	5.33	0.14			6.15	
Minimum safety factor		5.06	-2.94	3.14	5.22	1.70	

SAFETY FACTOR DESIGN CRITERIA
Kriel Colliery all sites



Site 3 layer 2 stabilised

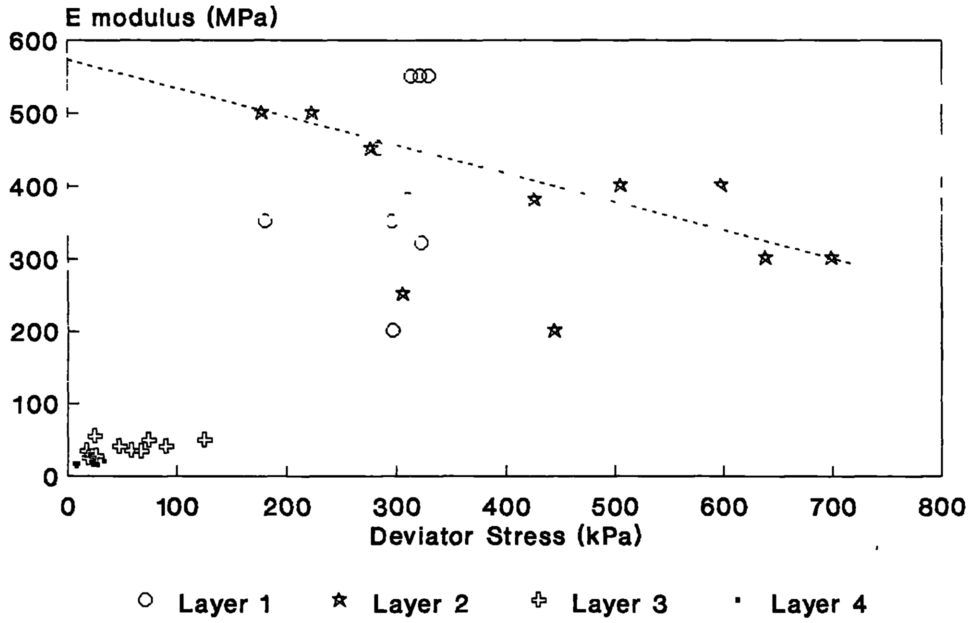
VERTICAL STRAIN DESIGN CRITERIA
Kriel Colliery all three sites



Site 3 layer 2 stabilised

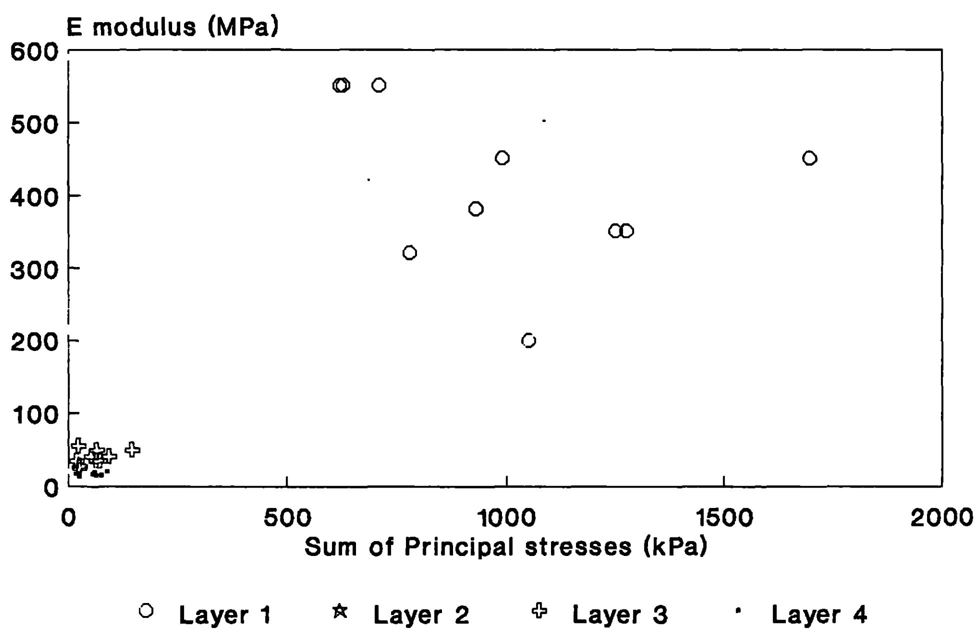
PAVEMENT LAYER STRESS SENSITIVITY

Kriel Site 1 all layers



PAVEMENT LAYER STRESS SENSITIVITY

Kriel Site 1 all layers



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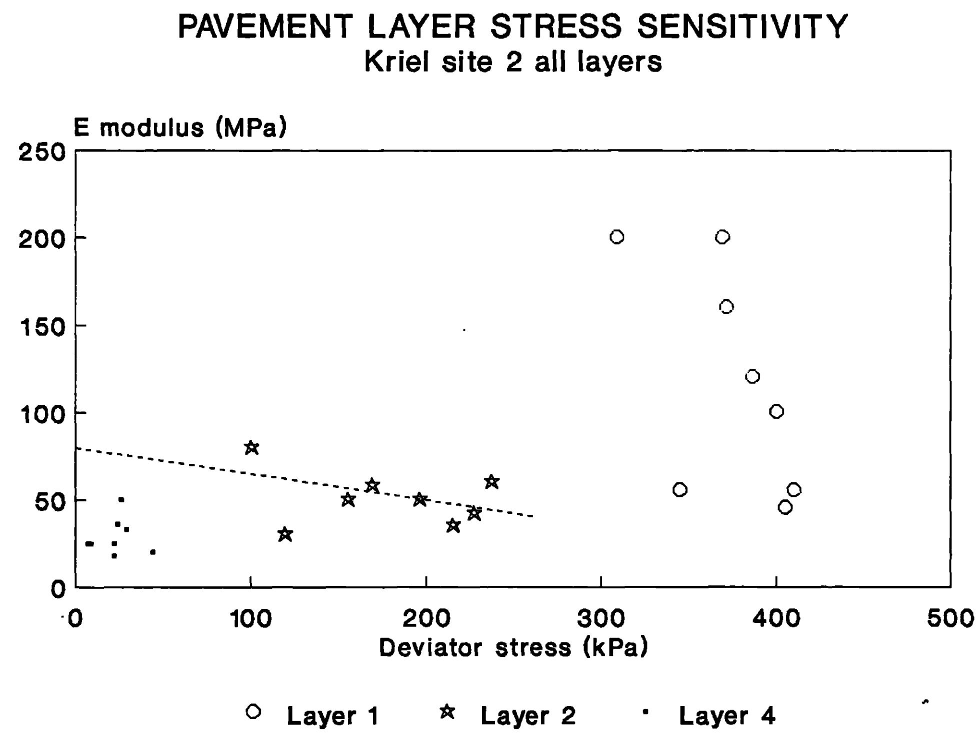

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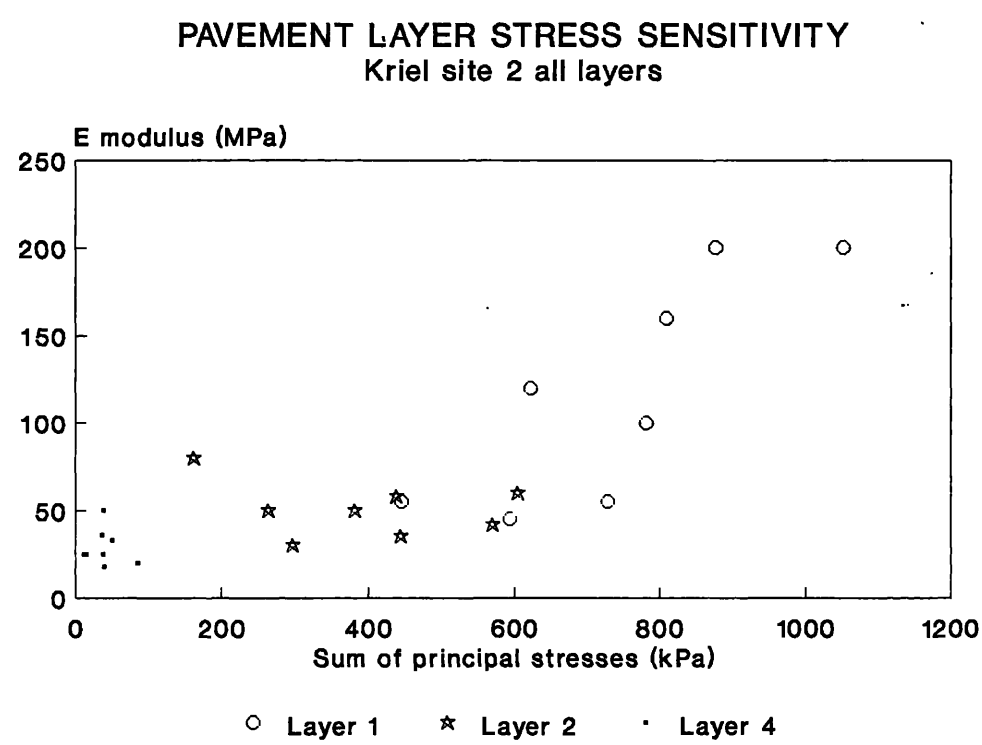

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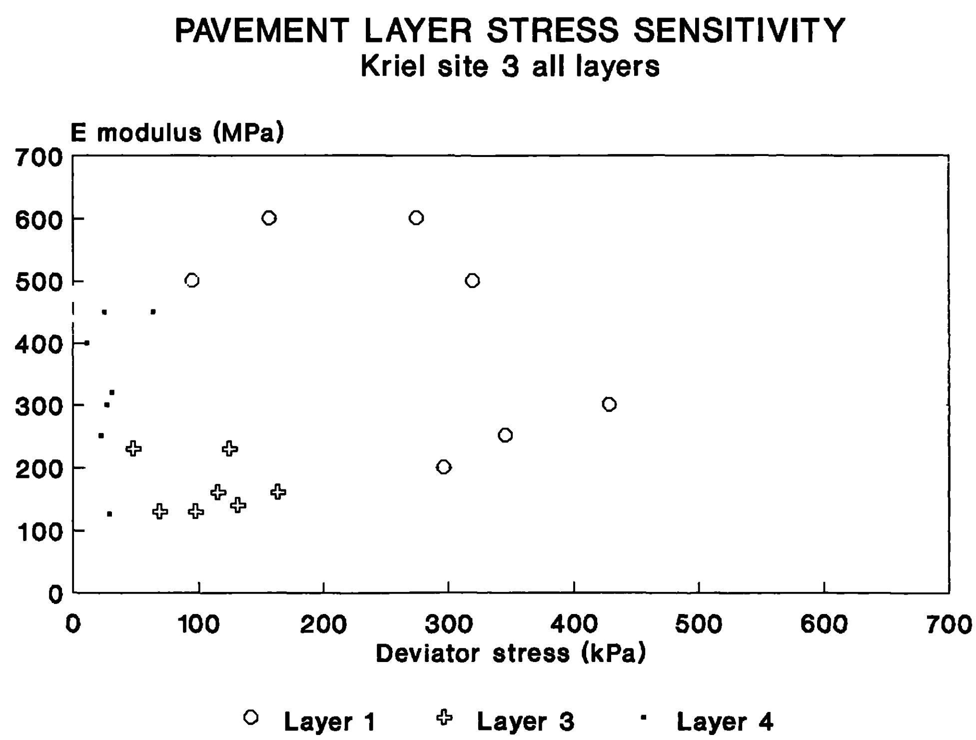

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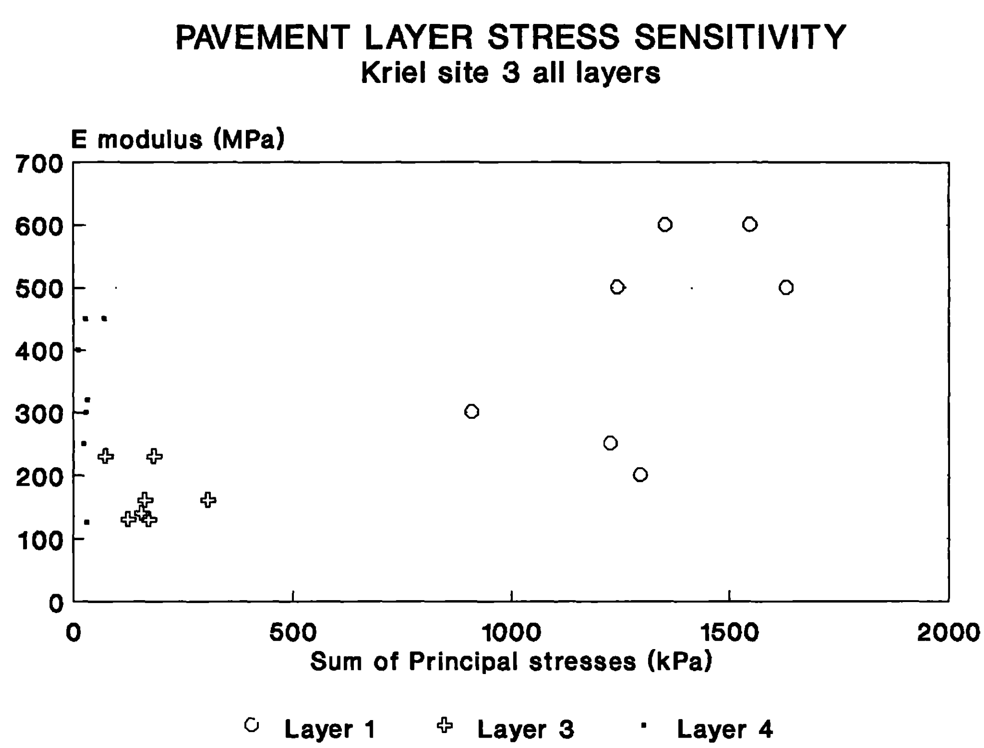


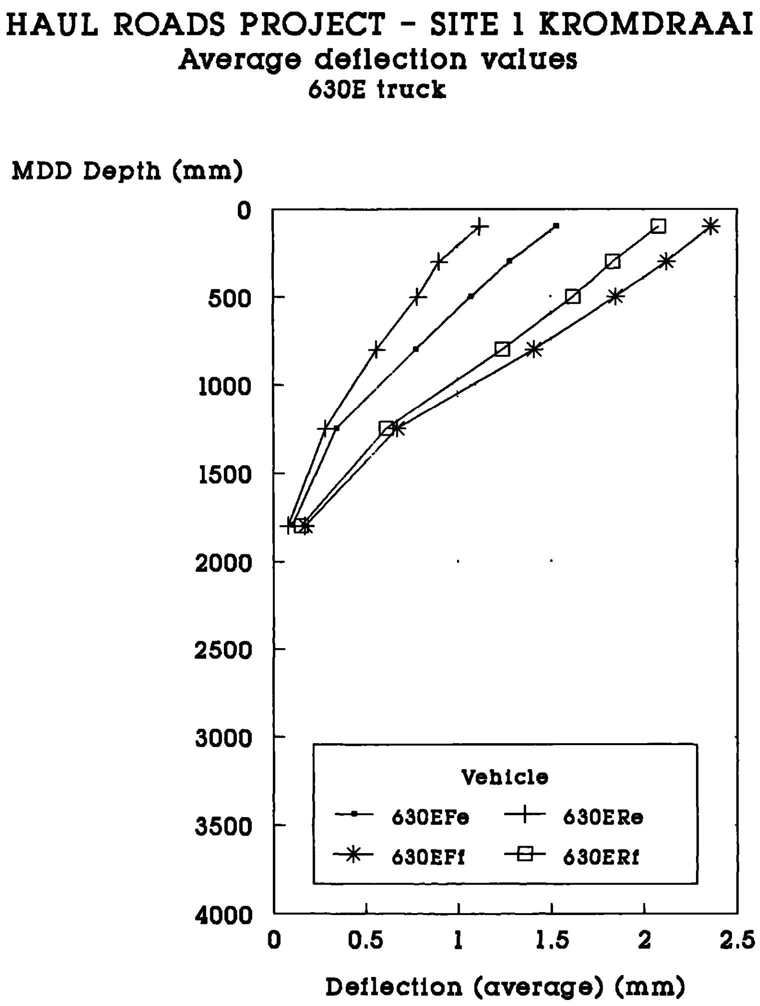
Stabilised layer 2 omitted

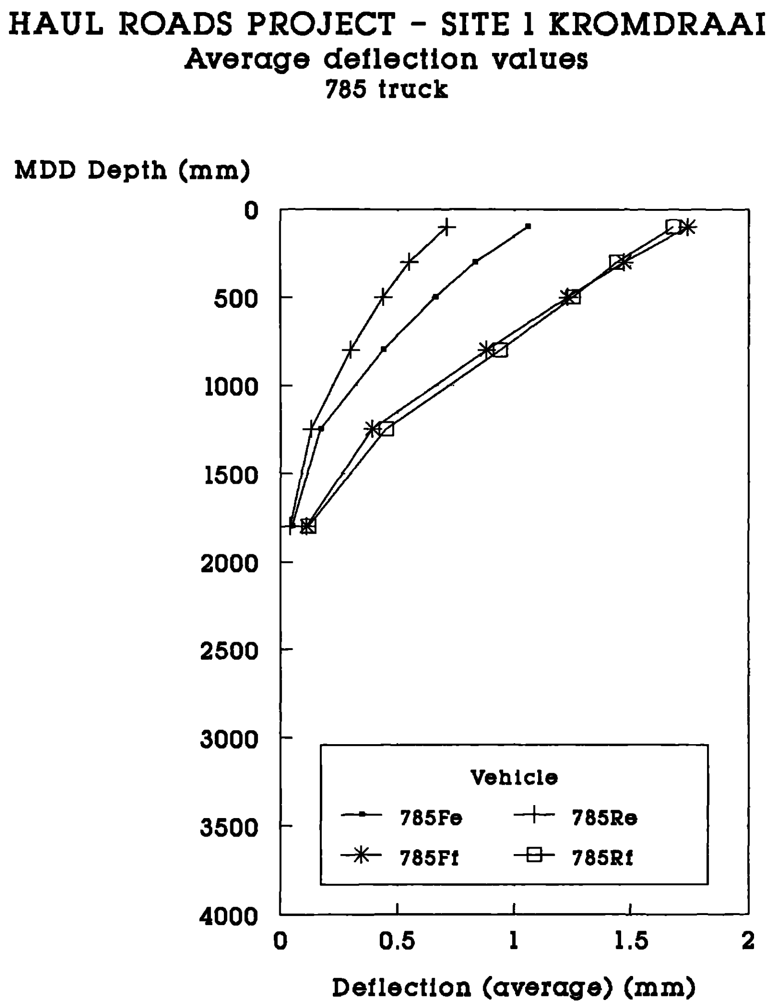
APPENDIX D2

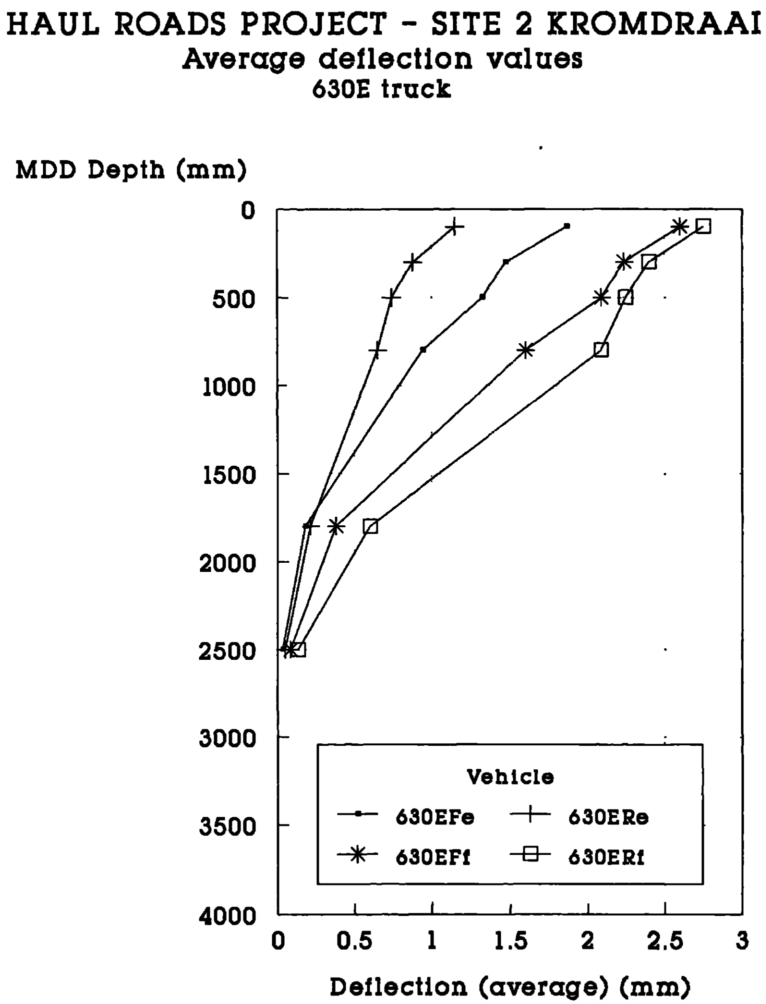
<u>RESULTS OF MDD AND MECHANISTIC ANALYSIS - KROMDRAAI COLLIERY</u>

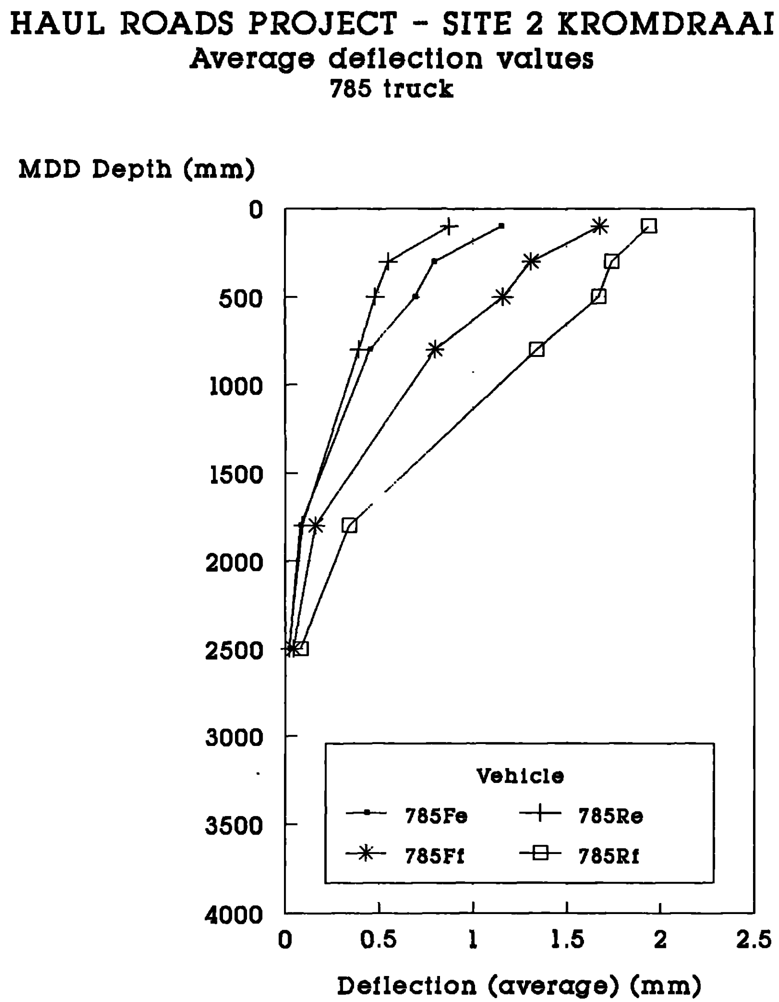
D2-2

Contents


HAUL ROADS PROJECT - SITE 1 KROMDRAAI
Average deflection values
630E truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.5
1
1.5
2
2.5
Deflection (average) (mm)
Vehicle
630EFe
630ERe
630EFf
630ERf


HAUL ROADS PROJECT - SITE 1 KROMDRAAI
Average deflection values
785 truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.5
1
1.5
2
Deflection (average) (mm)
Vehicle
785Fe
785Re
785Ff
785Rf


HAUL ROADS PROJECT - SITE 2 KROMDRAAI
Average deflection values
630E truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.5
1
1.5
2
2.5
3
Deflection (average) (mm)
Vehicle
630EFe
630ERe
630EFf
630ERf


HAUL ROADS PROJECT - SITE 2 KROMDRAAI
Average deflection values
785 truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.5
1
1.5
2
2.5
Deflection (average) (mm)
Vehicle
785Fe
785Re
785Ff
785Rf

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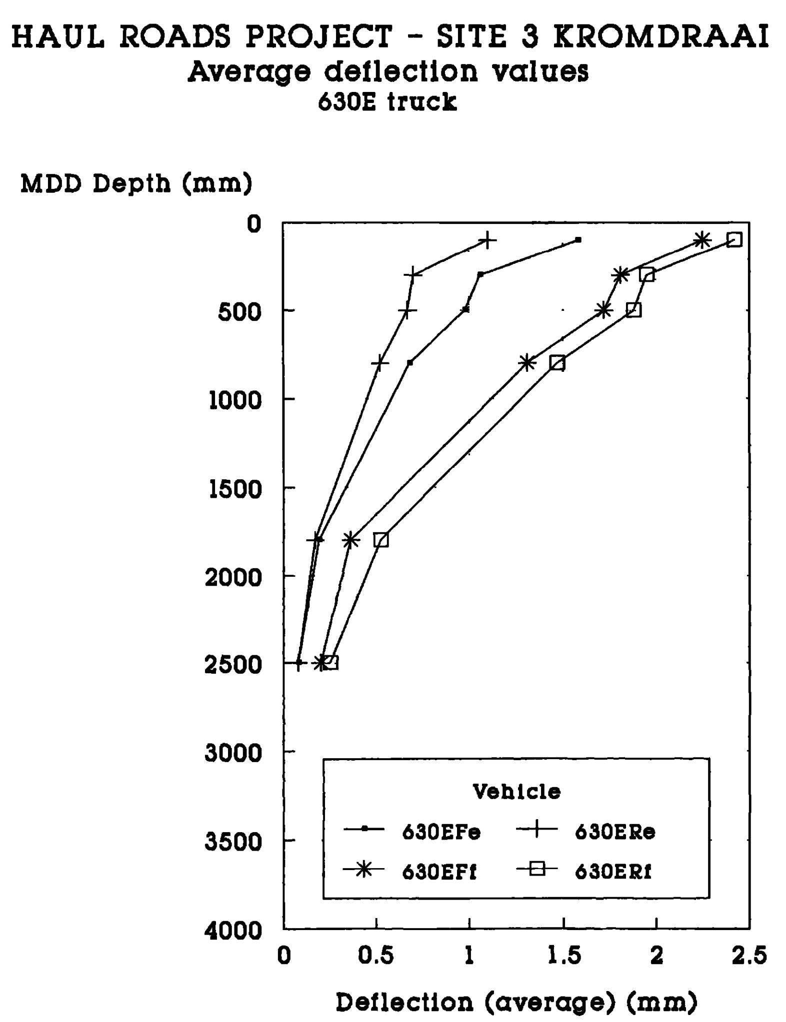

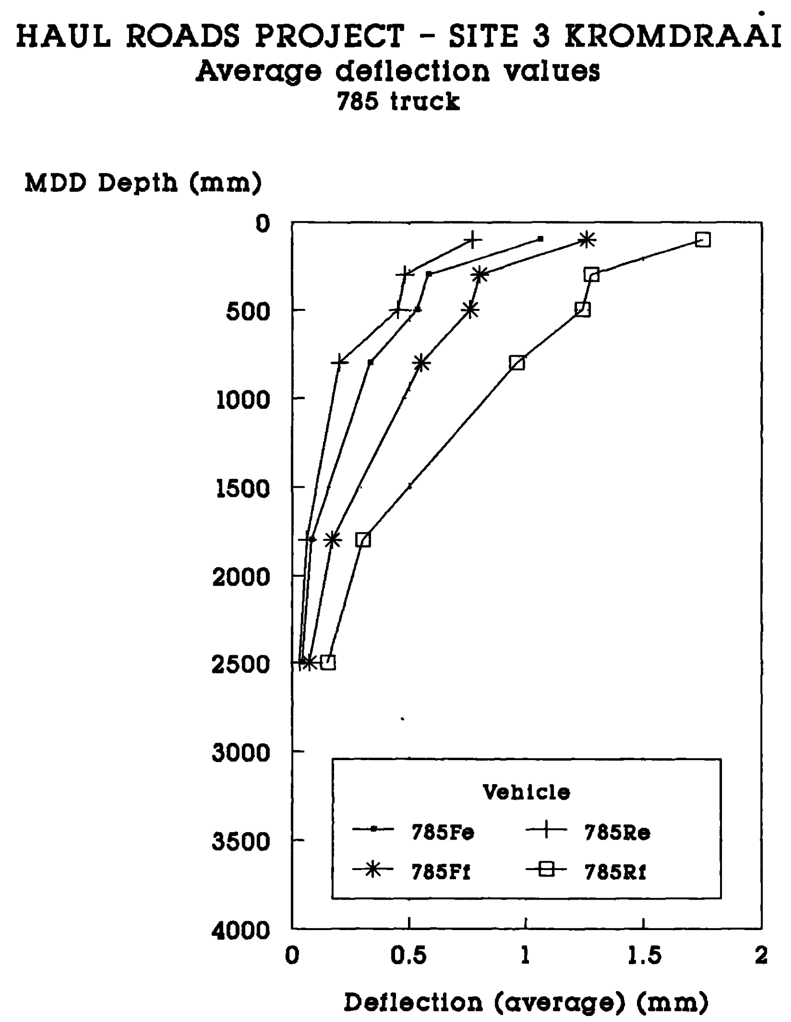

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	1
TRUCK TYPE	630E
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.53	1.52	165.0	1363.0	257.7	
2	■300 ■500	1.28 1.07	1.29 1.24	1490.0	152.9	384.4	926.9
3	■800	0.77	0.77	40.0	118.7	59.3	1990
4	■1250 ■1800	0.34 0.10	0.34 0.09	93.0	62.4	38.5	649.6

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MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	1
TRUCK TYPE	630E
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	2.36	2.36	180	1510.0	171.3	
2	■300 ■500	2.12 1.85	2.18 2.13	1540	107.4	435.2	170.9
3	■800	1.41	1.41	32	153.2	74.3	298.1
4	■1250 ■1800	0.68 0.20	0.67 0.18	63	87.1	50.8	1226.0

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	1
TRUCK TYPE	630E
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN $(x10^{-3})$ ε_v
1	■100	1.02	1.04	350	1236.0	310.1	
2	■300 ■500	0.90 0.82	0.89 0.80	620	119.3	302.2	601.0
3	■800	0.55	0.54	68	96.1	60.8	1257.0
4	■1250 ■1800	0.28 0.08	0.27 0.08	106	57.8	36.8	489.9

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	1
TRUCK TYPE	630E
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	2.08	2.05	240	1493.0	226.2	
2	■300 ■500	1.83 1.62	1.84 1.79	750	288.3	467.4	306.6
3	■800	1.24	1.24	84	309.5	167.4	2494.0
4	■1250 ■1800	0.61 0.18	0.62 0.17	146	179.7	115.3	1117.0

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MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	1
TRUCK TYPE	785
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.06	1.06	200	1229.0	327.1	
2	■300 ■500	0.83 0.66	0.83 0.76	840	103.8	298.8	344.9
3	■800	0.44	0.43	38	73.4	39.1	1492.0
4	■1250 ■1800	0.17 0.05	0.16 0.04	114	34.5	23.4	336.6

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	1
TRUCK TYPE	785
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.74	1.73	160	1341	275.5	
2	■300 ■500	1.47 1.23	1.48 1.42	1346	1001	359.2	17.41
3	■800	0.88	0.89	22	80.4	37.0	2242.0
4	■1250 ■1800	0.39 0.11	0.39 0.11	55	44.6	22.2	718.3

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	1
TRUCK TYPE	785
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	0.71	0.71	260	1042.0	391.0	
2	■300 ■500	0.55 0.41	0.52 0.47	810	96.1	225.0	421.3
3	■800	0.30	0.30	63	69.2	37.2	803.8
4	■1250 ■1800	0.13 0.04	0.14 0.04	138	36.0	23.9	264.1

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	1
TRUCK TYPE	785
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.50	1.52	420	1409.0	245.4	
2	■300 ■500	1.45 1.39	1.44 1.37	710	49.8	372.4	46.8
3	■800	0.93	0.93	45	129.0	69.9	1928.0
4	■1250 ■1800	0.45 0.12	0.45 0.12	83	73.6	45.7	827.1

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MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	2
TRUCK TYPE	630E
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1				100	1461.0	207.7	
2	■100 ■300	1.87 1.47	1.86 1.62	310	560.9	389.2	882.2
3	■500 ■800	1.32 0.94	1.32 0.76	97	178.7	150.5	2563.0
4	■1800 ■2500	0.18 0.03	0.18 0.03	158	45.1	40.9	684.8

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	2
TRUCK TYPE	630E
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1				100	1532.0	173.6	
2	■100 ■300	2.60 2.24	2.60 2.42	350	671.2	387.6	530.1
3	■500 ■800	2.09 1.60	2.09 1.39	98	214.1	197.2	3023.0
4	■1800 ■2500	0.38 0.08	0.38 0.07	104	64.2	55.5	1331.0

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	2
TRUCK TYPE	630E
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1				100	1337.0	272.7	
2	■100 ■300	1.15 0.80	1.15 0.92	342	496.3	341.1	1054.0
3	■500 ■800	0.74 0.65	0.75 0.68	220	71.5	116.2	915.9
4	■1800 ■2500	0.21 0.05	0.21 0.04	97	36.8	28.5	570.1

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MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	2
TRUCK TYPE	630E
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1				100	1487.0	209.8	
2	■100 ■300	2.75 2.40	2.76 2.55	338	775.2	384.5	704.9
3	■500 ■800	2.25 2.09	2.25 1.80	137	257.4	247.2	2416.0
4	■1800 ■2500	0.60 0.13	0.60 0.12	110	114.7	91.5	1504.0

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	2
TRUCK TYPE	785
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1				100	1357.0	258.1	
2	■100 ■300	1.15 0.79	1.14 0.89	310	372.1	334.1	1121.0
3	■500 ■800	0.69 0.45	0.69 0.36	91	92.8	79.6	1638.0
4	■1800 ■2500	0.08 0.02	0.08 0.01	176	21.2	20.1	314.9

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	2
TRUCK TYPE	785
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1				100	1437.0	218.7	
2	■100 ■300	1.68 1.31	1.69 1.44	300	492.1	374.5	983.4
3	■500 ■800	1.16 0.80	1.16 0.67	90	138.3	121.6	2337.0
4	■1800 ■2500	0.16 0.04	0.16 0.03	138	34.6	31.7	614.4

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	2
TRUCK TYPE	785
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1				100	1274.0	307.7	
2	■100 ■300	0.87 0.55	0.87 0.62	294	306.4	280.3	1384.0
3	■500 ■800	0.48 0.39	0.48 0.32	130	74.7	60.9	926.7
4	■1800 ■2500	0.09 0.02	0.09 0.02	160	23.7	20.8	284.1

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	2
TRUCK TYPE	785
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1				100	1424.0	233.5	
2	■100 ■300	1.94 1.74	1.94 1.79	450	431.4	362.2	490.6
3	■500 ■800	0.67 1.34	1.65 1.16	68	149.6	108.7	2288.0
4	■1800 ■2500	0.34 0.08	0.34 0.06	91	52.5	43.3	960.8

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	3
TRUCK TYPE	630E
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.58	1.58	52	1282.0	296.5	
2	■300 ■500	1.06 0.98	1.05 0.94	460	443.7	345.3	683.9
3	■800 ■1800 ■2500	0.68 0.19 0.08	0.68 0.22 0.09	153	32.9	33.1	1147.0

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	3
TRUCK TYPE	630E
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	2.25	2.25	54	1340.0	266.4	
2	■300 ■500	1.81 1.72	1.82 1.67	500	510.5	364.6	412.7
3	■800 ■1800 ■2500	1.31 0.36 0.20	1.31 0.46 0.19	108	49.2	46.7	1837.2

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	3
TRUCK TYPE	630E
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.10	1.10	61	1219.0	344.5	
2	■300 ■500	0.70 0.67	0.71 0.64	835	274.4	270.4	393.3
3	■800 ■1800 ■2500	0.52 0.17 0.08	0.52 0.23 0.09	123	30.1	26.1	685.2

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	3
TRUCK TYPE	630E
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	2.42	2.43	55	1330	277.0	
2	■300 ■500	1.95 1.88	1.95 1.75	395	611.5	385.5	734.5
3	■800 ■1800 ■2500	1.47 0.52 0.25	1.47 0.59 0.25	156	94.8	86.9	1645.0

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	3
TRUCK TYPE	785
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.06	1.06	58	1215.0	344.0	
2	■300 ■500	0.58 0.53	0.59 0.47	480	288.0	271.0	810
3	■800 ■1800 ■2500	0.33 0.08 0.04	0.33 0.10 0.04	166	16.2	16.8	642.3

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	3
TRUCK TYPE	785
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	1.26	1.26	52	1254.0	313.9	
2	■300 ■500	0.80 0.76	0.81 0.71	688	356.1	313.8	442.7
3	■800 ■1800 ■2500	0.55 0.17 0.07	0.54 0.18 0.07	137	24.2	24.0	875.5

MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	3
TRUCK TYPE	785
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100	0.77	1.043	54	1124.0	395.7	
2	■300 ■500	0.48 0.45	0.48 0.36	331	210.3	201.7	1318.0
3	■800 ■1800 ■2500	0.27 0.06 0.03	0.27 0.10 0.04	195	18.8	18.6	423.4

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MINE	SACE KROMDRAAI COLLIERY
SITE NUMBER	3
TRUCK TYPE	785
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN $(x10^{-3})$ ε_v
1	■100	1.75	1.76	52	1256.0	319.1	
2	■300 ■500	1.28 1.24	1.27 1.20	450	355.9	308.0	734.2
3	■800 ■1800 ■2500	0.96 0.30 0.15	0.97 0.36 0.15	110	40.5	38.0	1158.0

SAFETY FACTOR ESTIMATION - SACE KROMDRAAI COLLIERY

C-TERM = 223

Phi-TERM 5.5

Minor principle stress (kPa)		Site 1 layer 1	Site 1 layer 2	Site 2 layer 1	Site 2 layer 2	Site 3 layer 1	Site 3 layer 2
630E	FF	617	326	626	482	624	413
	FE	626	307	625	446	624	378
	RF	617	392	628	510	625	454
	RE	612	234	625	392	634	269
785	FF	630	272	624	413	627	327
	FE	627	233	624	346	634	276
	RF	613	252	623	379	629	318
	RE	604	177	627	286	616	184
Deviator stress (kPa)							
630E	FF	171	435	173	387	266	364
	FE	257	384	207	389	296	345
	RF	226	467	209	384	277	385
	RE	310	302	272	341	344	270
785	FF	275	359	218	374	313	313
	FE	327	299	258	334	344	271
	RF	245	372	233	362	319	308
	RE	391	225	307	280	395	201

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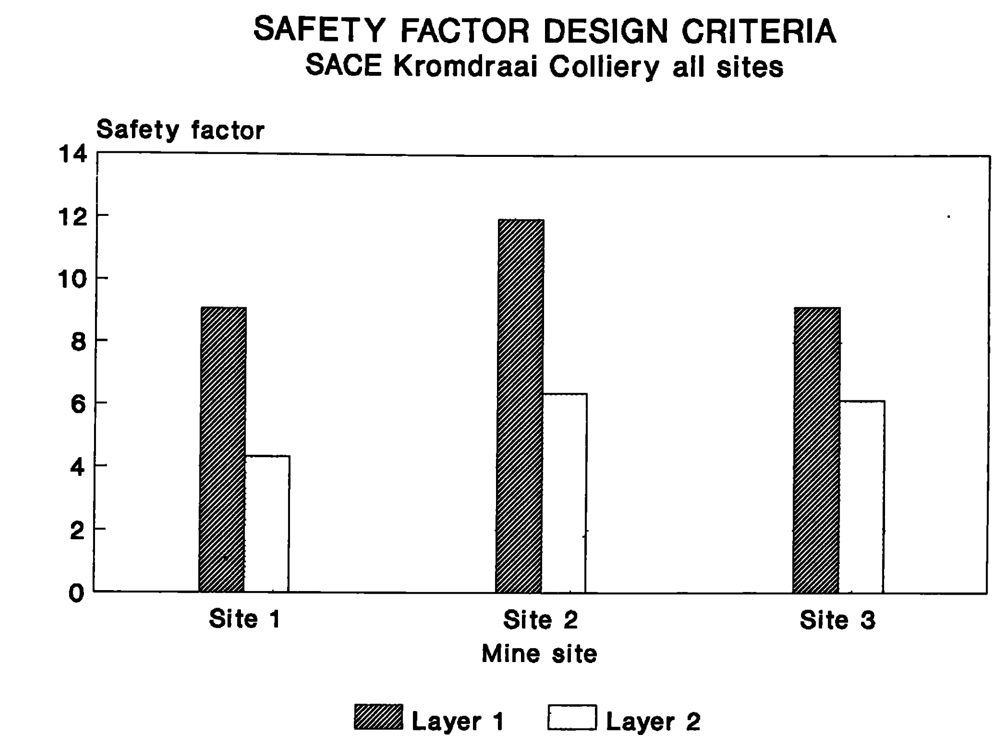
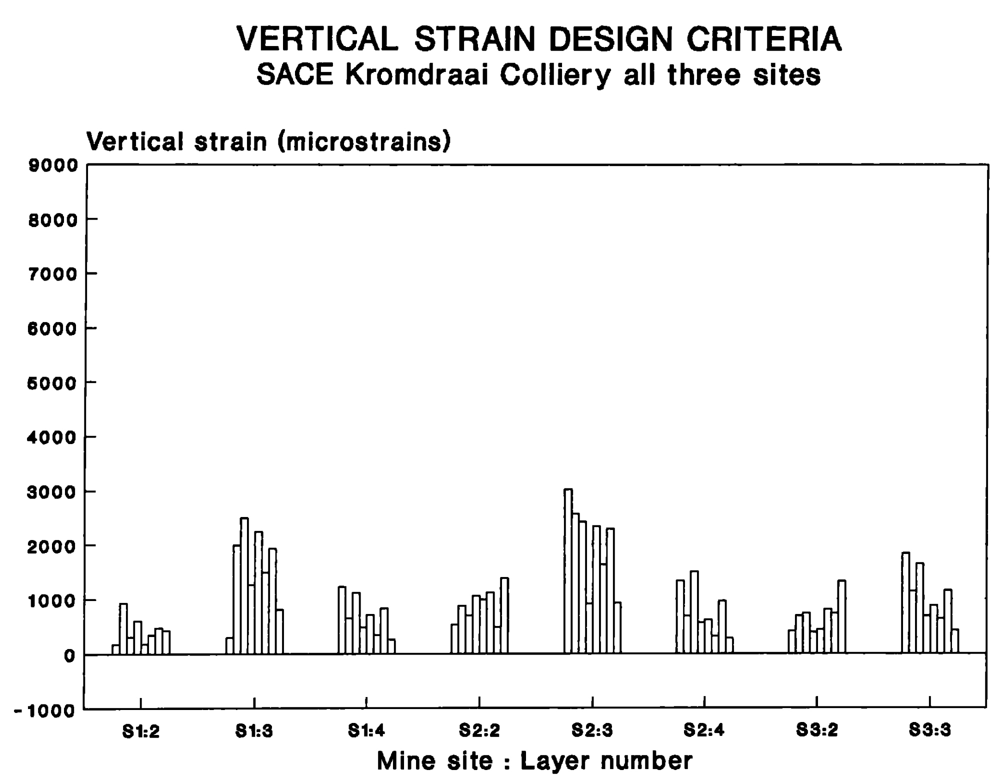
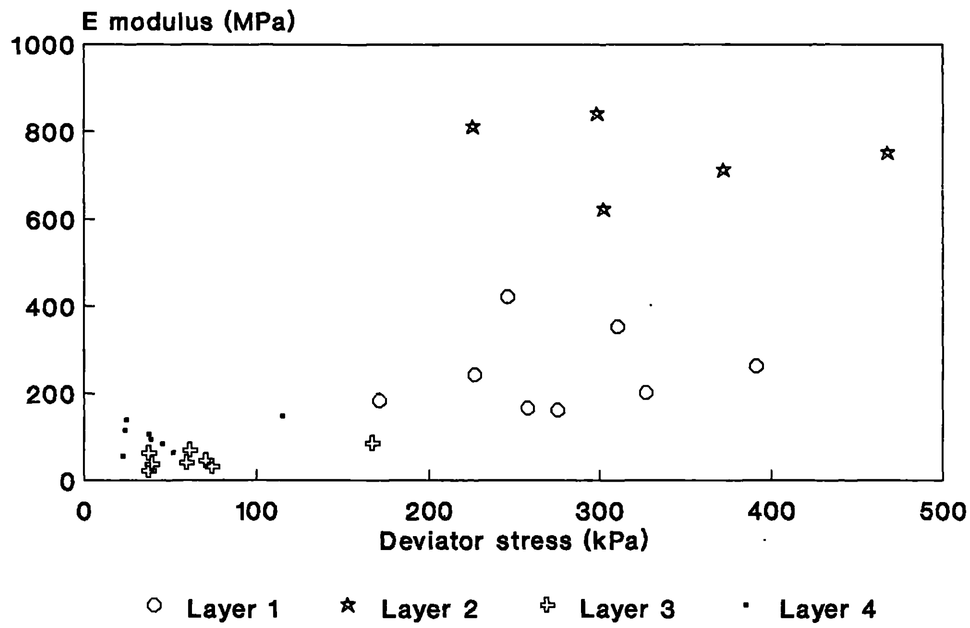
Safety factor							
630E	FF	21.15	4.63	21.19	7.43	13.74	6.35
	FE	14.26	4.98	17.68	6.88	12.35	6.67
	RF	16.00	5.09	17.59	7.89	13.21	7.06
	RE	11.18	5.00	13.46	6.98	10.78	6.31
785	FF	13.41	4.79	16.77	6.67	11.73	6.26
	FE	11.23	5.03	14.17	6.37	10.78	6.42
	RF	14.67	4.33	15.66	6.37	11.54	6.40
	RE	9.07	5.32	11.96	6.41	9.74	6.14
Minimum safety factor		9.07	4.33	11.96	6.37	9.14	6.14

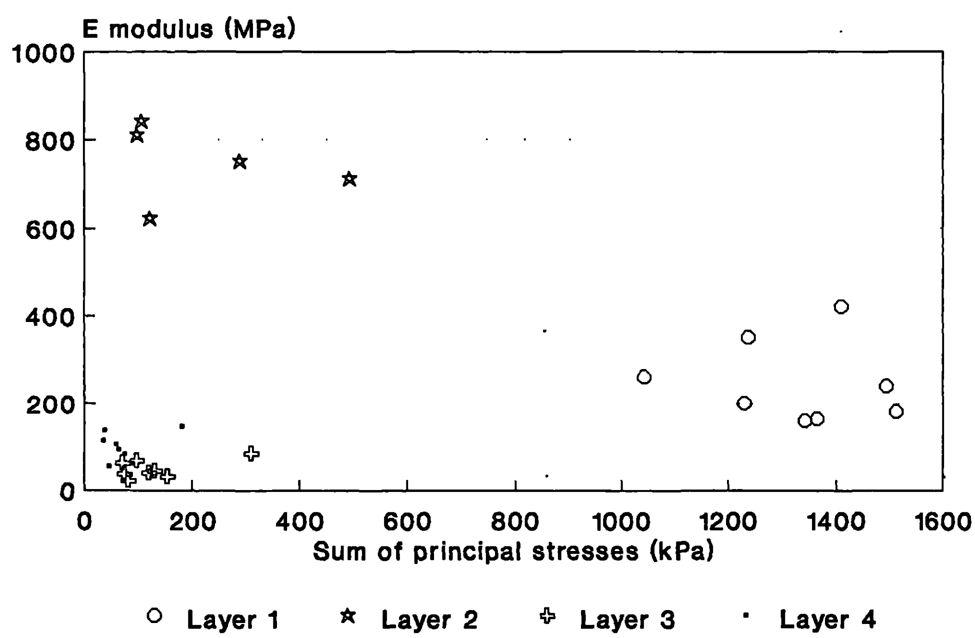

SAFETY FACTOR DESIGN CRITERIA
SACE Kromdraai Colliery all sites
Safety factor
14
12
10
8
6
4
2
0
Site 1
Site 2
Site 3
Mine site
Layer 1
Layer 2

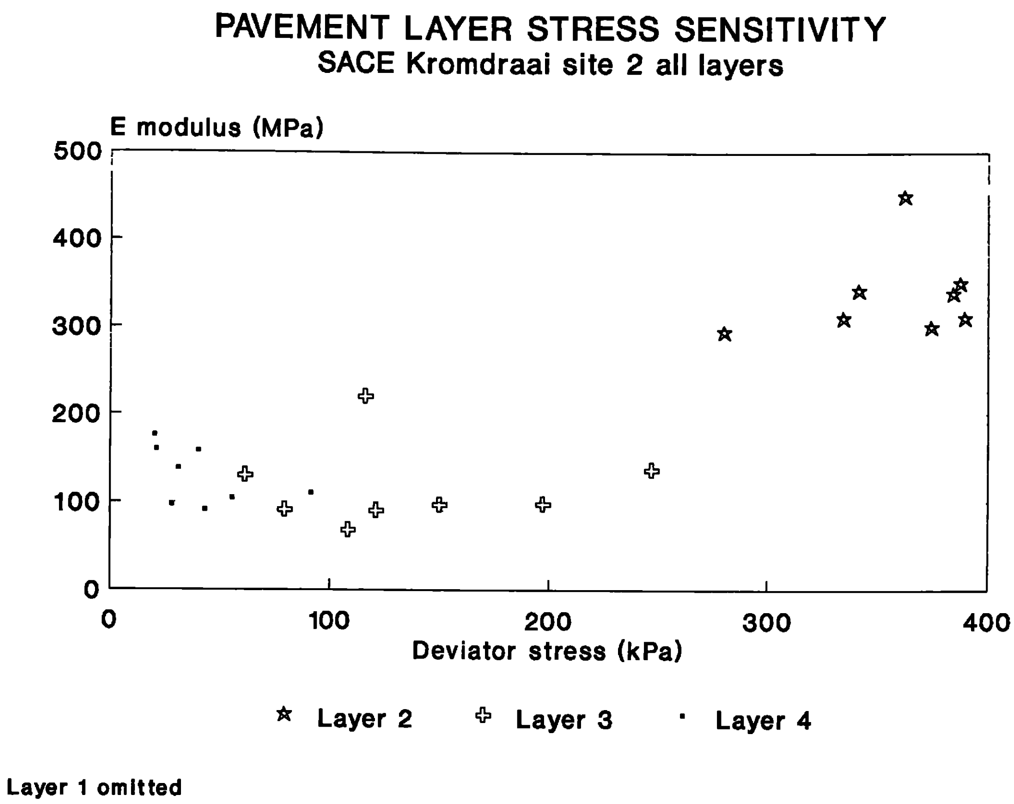

VERTICAL STRAIN DESIGN CRITERIA
SACE Kromdraai Colliery all three sites
Vertical strain (microstrains)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
S1:2
S1:3
S1:4
S2:2
S2:3
S2:4
S3:2
S3:3
Mine site : Layer number

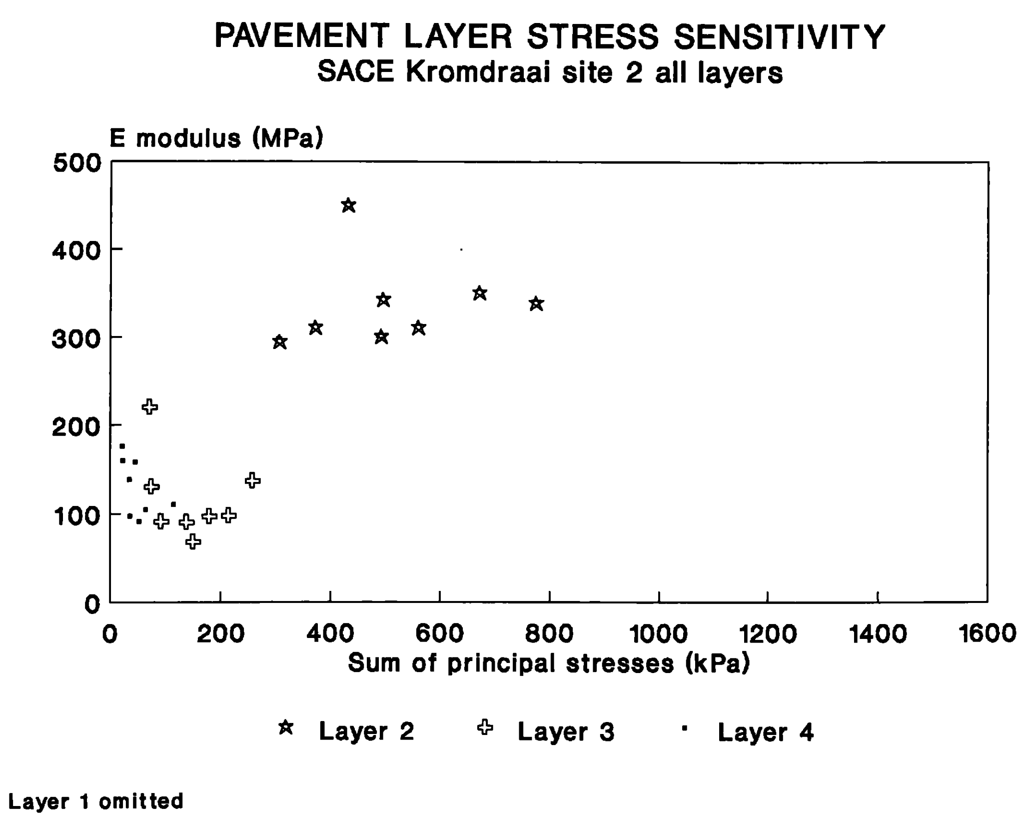
PAVEMENT LAYER STRESS SENSITIVITY
SACE Kromdraai site 1 all layers

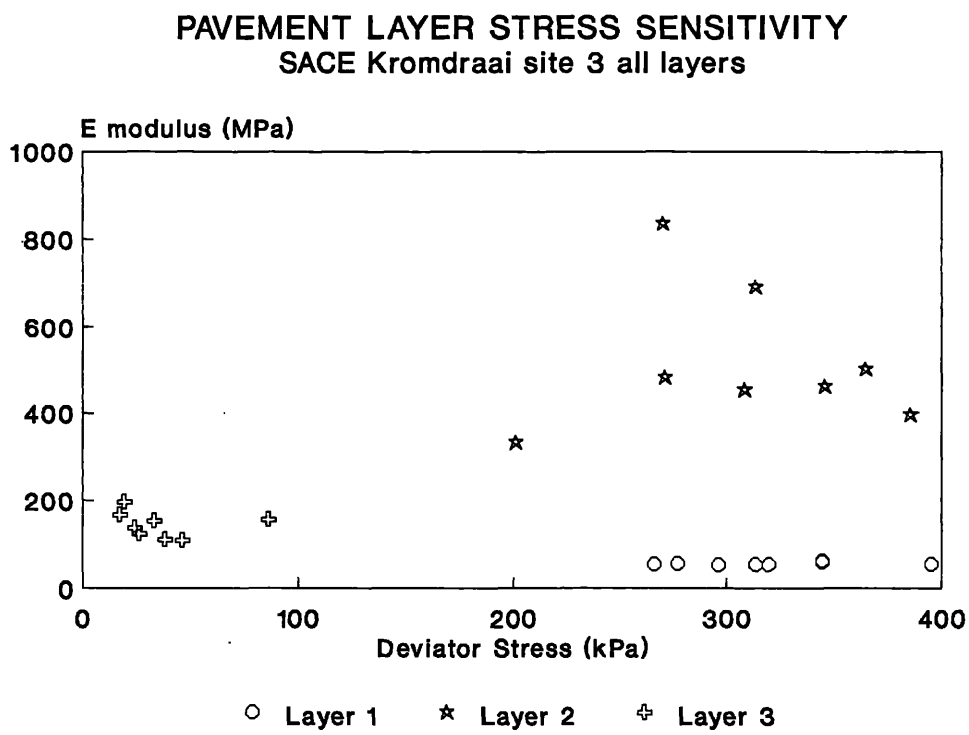


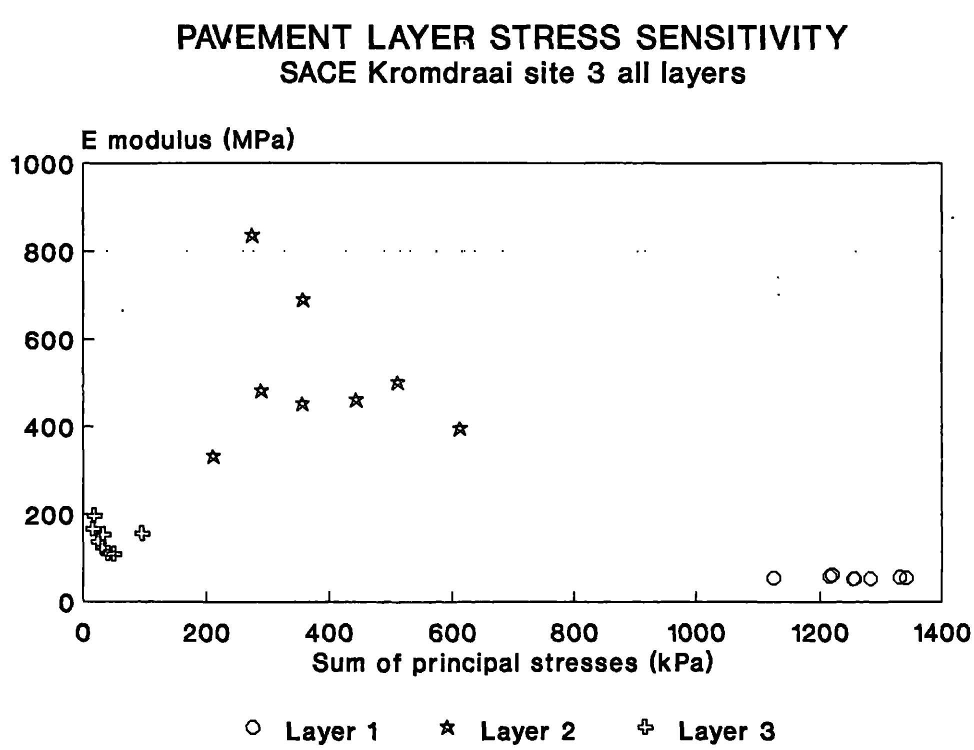
PAVEMENT LAYER STRESS SENSITIVITY
SACE Kromdraai site 1 all layers




PAVEMENT LAYER STRESS SENSITIVITY
SACE Kromdraai site 2 all layers
E modulus (MPa)
500
400
300
200
100
0
0
100
200
300
400
Deviator stress (kPa)
Layer 2
Layer 3
Layer 4
Layer 1 omitted


PAVEMENT LAYER STRESS SENSITIVITY
SACE Kromdraai site 2 all layers
E modulus (MPa)
500
400
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
Sum of principal stresses (kPa)
Layer 2
Layer 3
Layer 4
Layer 1 omitted


PAVEMENT LAYER STRESS SENSITIVITY
SACE Kromdraai site 3 all layers
E modulus (MPa)
1000
800
600
400
200
0
0
100
200
300
400
Deviator Stress (kPa)
Layer 1
Layer 2
Layer 3


PAVEMENT LAYER STRESS SENSITIVITY
SACE Kromdraai site 3 all layers
E modulus (MPa)
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
Sum of principal stresses (kPa)
Layer 1
Layer 2
Layer 3

APPENDIX D3

RESULTS OF MDD AND MECHANISTIC ANALYSIS - NEW VAAL COLLIERY

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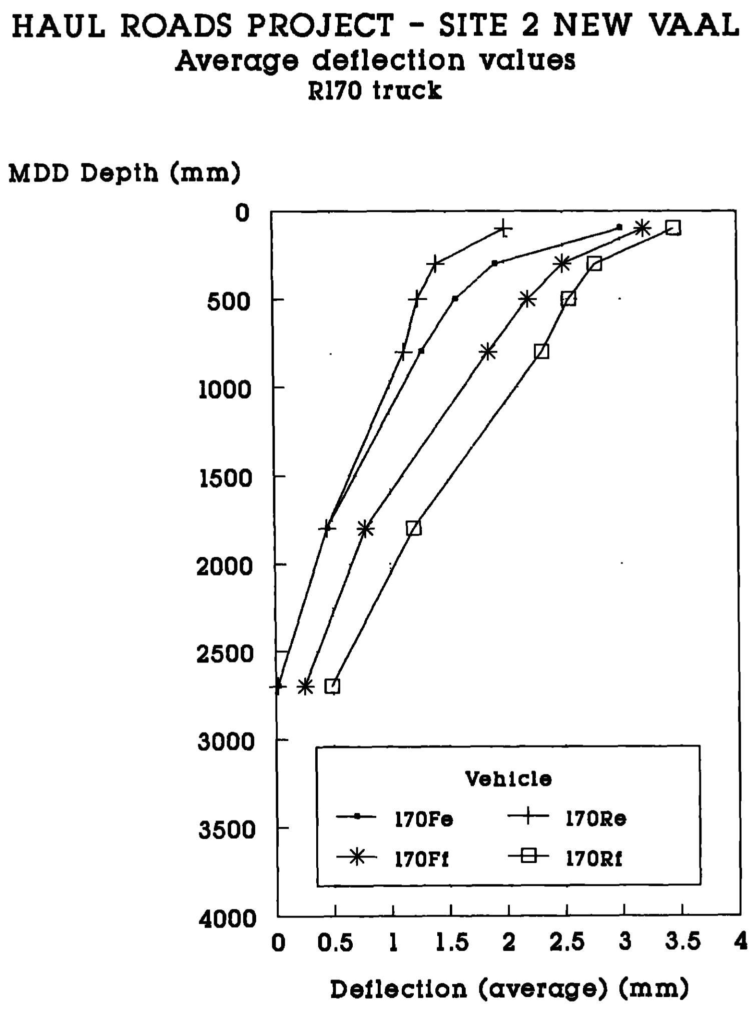
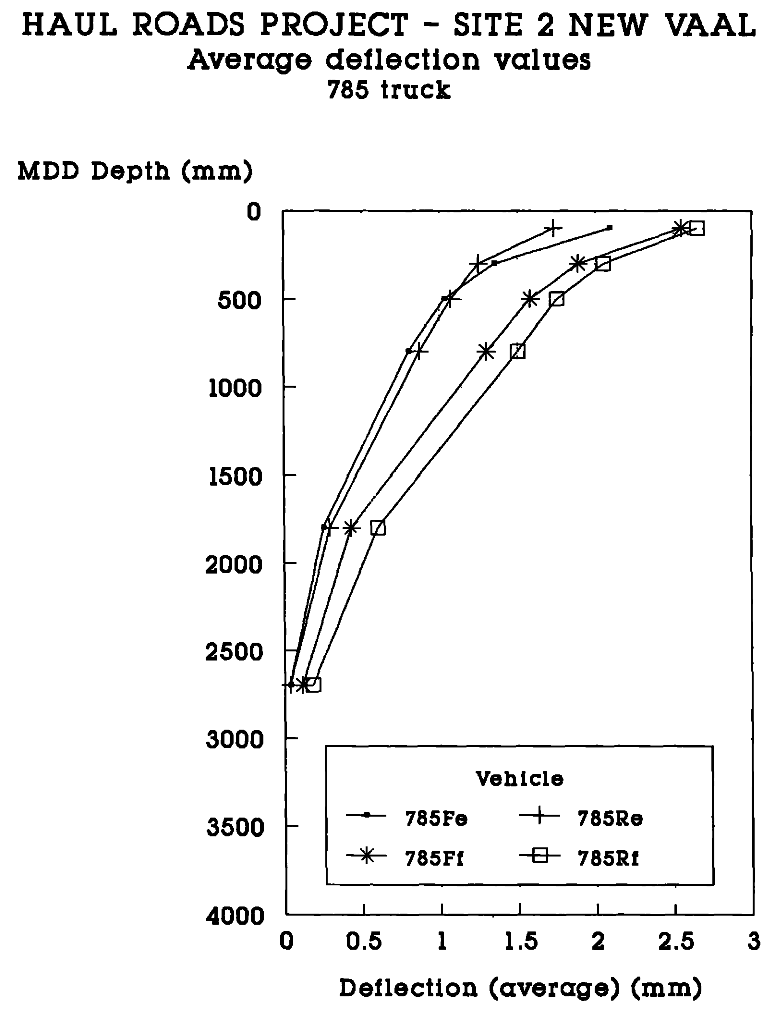
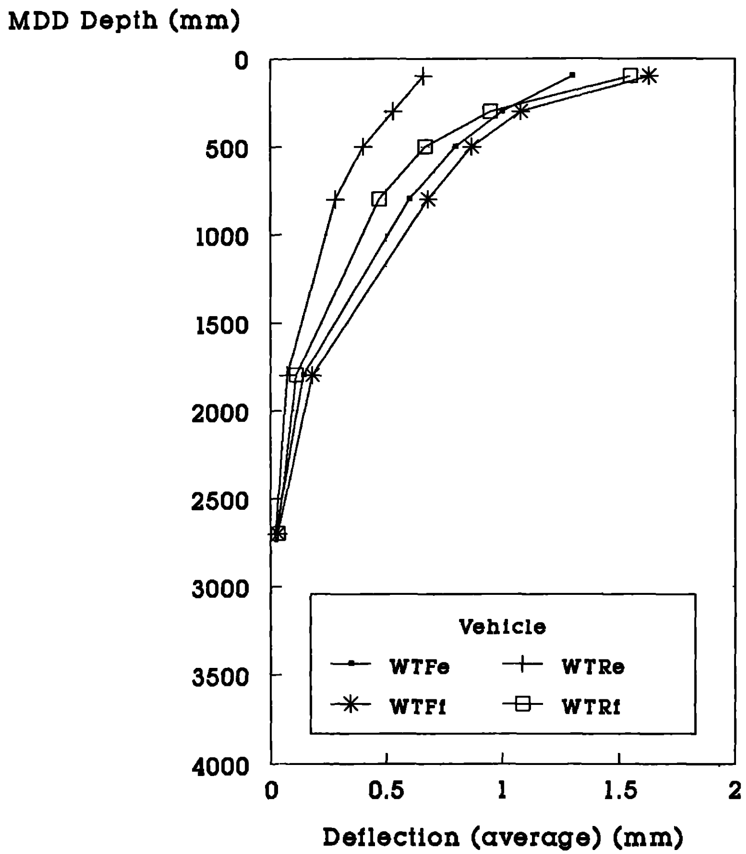
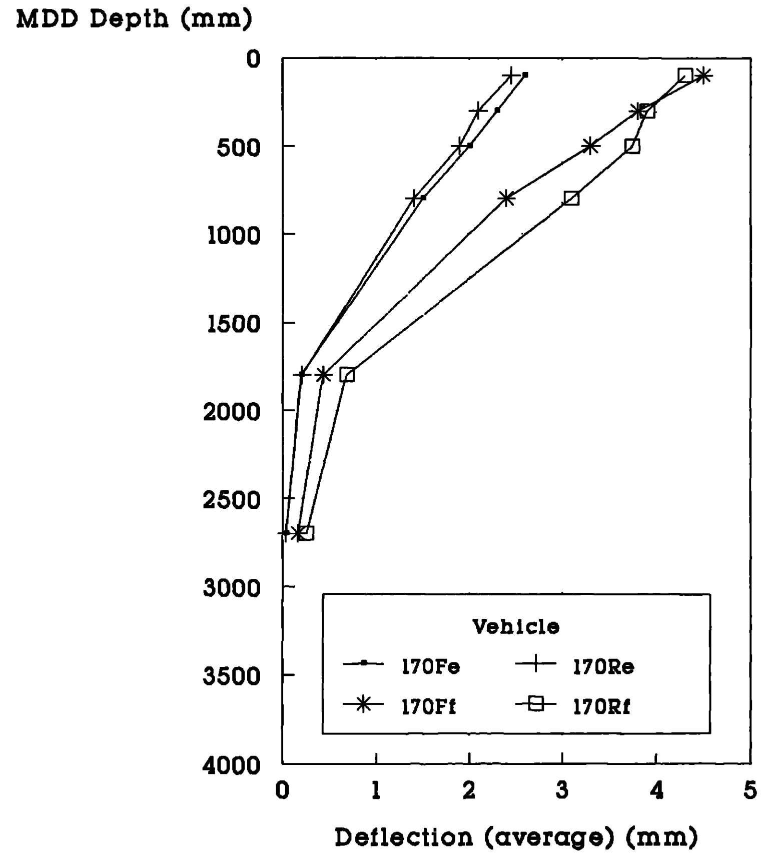

HAUL ROADS PROJECT - SITE 2 NEW VAAL
Average deflection values
R170 truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.5
1
1.5
2
2.5
3
3.5
4
Deflection (average) (mm)
Vehicle
170Fe
170Re
170Ff
170Rf

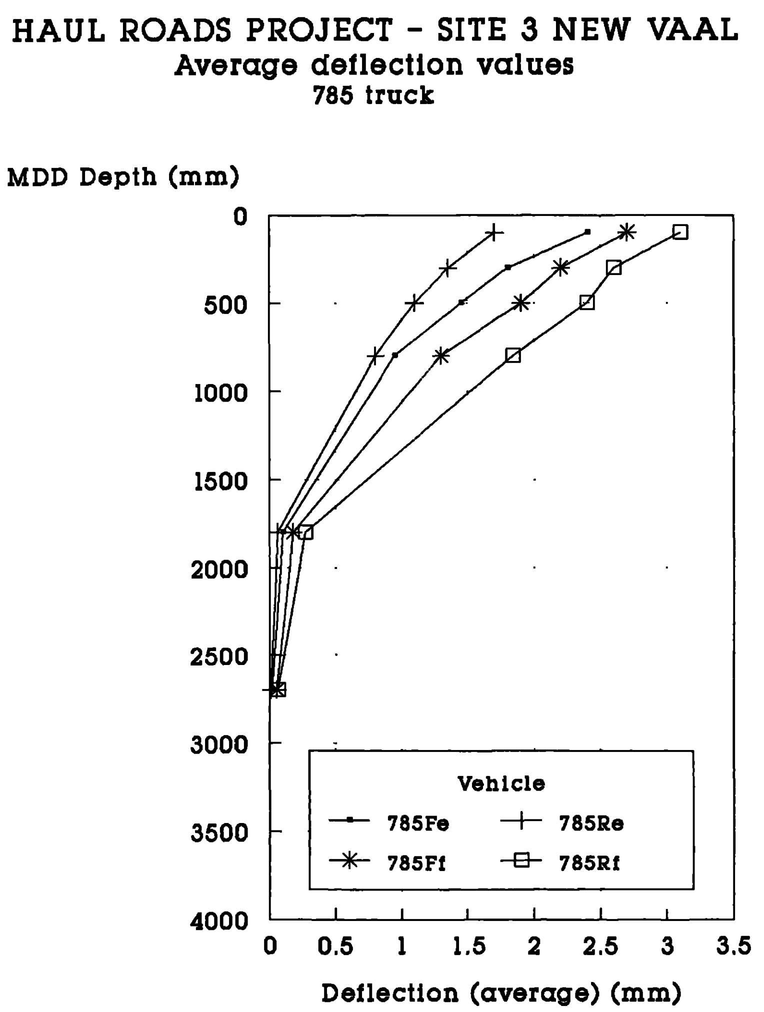

HAUL ROADS PROJECT - SITE 2 NEW VAAL
Average deflection values
785 truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.5
1
1.5
2
2.5
3
Deflection (average) (mm)
Vehicle
785Fe
785Re
785Ff
785Rf

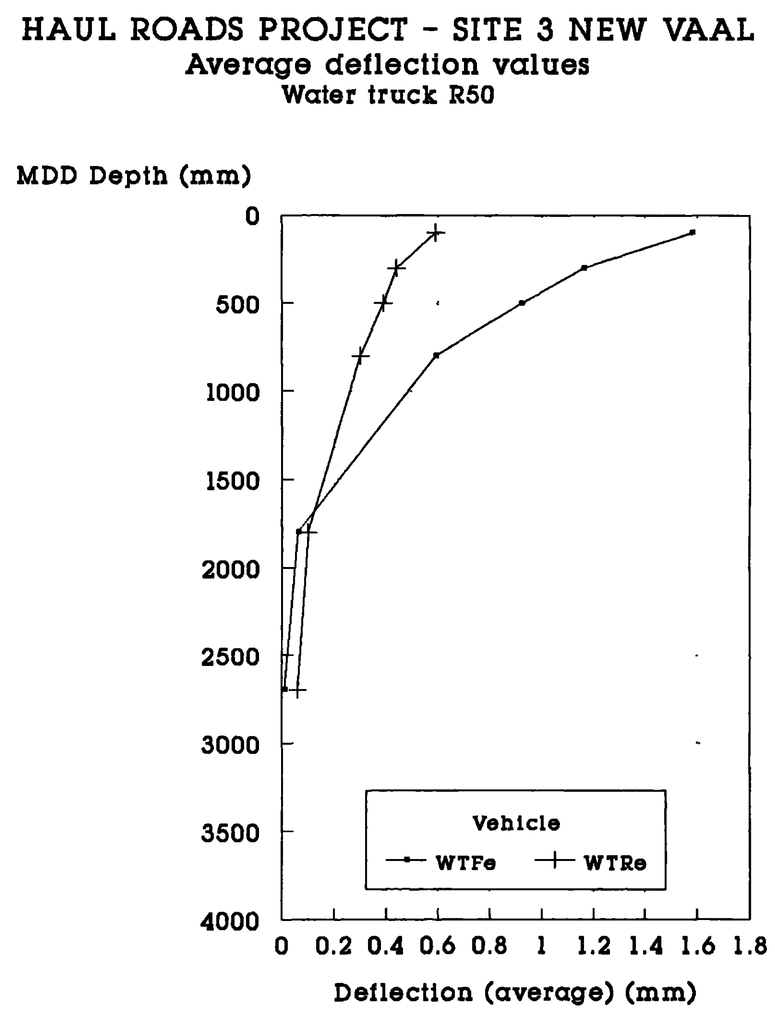
HAUL ROADS PROJECT - SITE 2 NEW VAAL
Average deflection values
Water truck R50



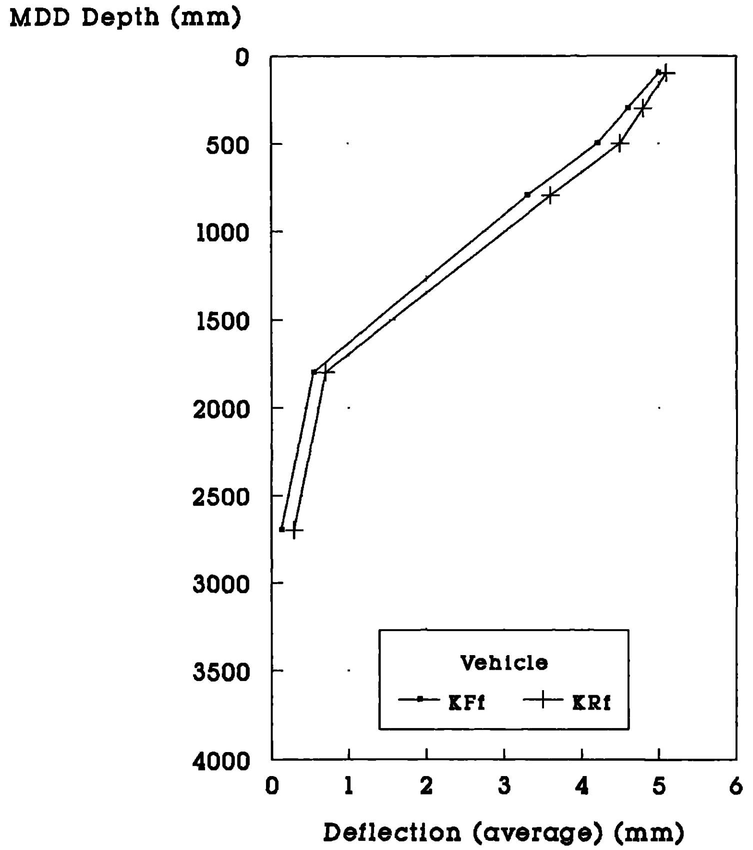
HAUL ROADS PROJECT - SITE 3 NEW VAAL
Average deflection values
R170 truck




HAUL ROADS PROJECT - SITE 3 NEW VAAL
Average deflection values
785 truck
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.5
1
1.5
2
2.5
3
3.5
Deflection (average) (mm)
Vehicle
785Fe
785Re
785Ff
785Rf


HAUL ROADS PROJECT - SITE 3 NEW VAAL
Average deflection values
Water truck R50
MDD Depth (mm)
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Deflection (average) (mm)
Vehicle
WTFe
WTRe

HAUL ROADS PROJECT - SITE 3 NEW VAAL
Average deflection values
KOMATSU (170t)



MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	R170
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN $(x10^{-3})$ ε_v
1	■100 ■300 ■500	3.00 1.92 1.57	2.35 1.91 1.57	190	201.2	212.9	
2	■800	1.28	1.27	31	36.1	25.8	1727
3	■1800 ■2800	0.45 0.15	0.45 0.09	61	21.8	14.1	367.6

MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	R170
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	3.20 2.50 2.20	2.80 2.50 2.10	227	283.2	273.0	
2	■800	1.85	1.84	34	50.3	38.8	1644
3	■1800 ■2800	0.78 0.25	0.78 0.17	48	34.6	20.7	672.1

MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	R170
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	2.00 1.41 1.25	1.70 1.41 1.20	274	157.5	174.1	
2	■800	1.12	1.12	30	45.0	24.8	1065
3	■1800 ■2800	0.45 0.15	0.44 0.09	77	29.6	16.6	318.9

MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	R170
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	3.46 2.78 2.55	3.02 2.76 2.53	283	337.0	301.7	
2	■800	2.32	2.34	54	89.7	73.0	1714
3	■1800 ■2800	1.20 0.48	1.20 0.29	56	70.7	39.4	1047

MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	785
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	2.09 1.35 1.03	1.87 1.35 1.04	153	112.4	132.3	
2	■800	0.80	0.80	21	17.7	11.9	889.3
3	■1800 ■2800	0.25 0.03	0.25 0.04	54	10.5	6.3	191.7

MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	785
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	2.55 1.89 1.58	2.35 1.89 1.55	186	168.5	188.1	
2	■800	1.30	1.29	19	27.8	17.3	1372
3	■1800 ■2800	0.43 0.11	0.43 0.08	50	16.7	10.3	323.0

MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	785
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	1.73 1.25 1.07	1.85 1.25 1.00	113	72.5	83.8	
2	■800	0.87	0.88	20	21.2	13.0	908.9
3	■1800 ■2800	0.29 0.06	0.29 0.05	58.5	12.5	7.9	209.2

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MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	785
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	2.65 2.05 1.75	2.51 2.05 1.77	181	224.5	219.5	
2	■800	1.50	1.51	53	62.4	49.8	1316
3	■1800 ■2800	0.60 0.18	0.60 0.13	78	40.7	26.0	521.4

MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	WATER CAR
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	1.30 1.00 0.80	1.47 1.00 0.76	160	82.8	101.5	
2	■800	0.60	0.59	15	13.3	7.1	739.1
3	■1800 ■2800	0.14 0.02	0.14 0.018	100	8.1	4.2	68.53

MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	WATER CAR
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	1.63 1.08 0.87	1.35 1.08 0.82	240	109.5	133.1	
2	■800	0.68	0.68	15	15.9	8.2	819.6
3	■1800 ■2800	0.18 0.03	0.18 0.027	81	9.8	5.2	101.0

MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	WATER CAR
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN (x10^{-3}) ε_v
1	■100 ■300 ■500	0.66 0.53 0.38	0.90 0.53 0.38	158	58.5	64.5	
2	■800	0.28	0.28	64	16.6	12.8	298.8
3	■1800 ■2800	0.080 0.030	0.08 0.02	138	9.3	6.5	77.43

MINE	NEW VAAL COLLIERY
SITE NUMBER	2
TRUCK TYPE	WATER CAR
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	1.55 0.93 0.67	1.31 0.93 0.68	208	191.8	165.7	
2	■800	0.54	0.47	187	59.8	49.2	398.3
3	■1800 ■2800	0.13 0.03	0.12 0.02	430	30.6	23.2	90.18

MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	R170
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	2.60 2.30 2.00	2.70 2.30 1.96	180	382.9	328.4	
2	■800	1.50	1.50	30	86.6	54.2	2993
3	■1800 ■2800	0.19 0.03	0.19 0.04	176	30.6	24.6	270.4

MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	R170
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN $(x10^{-3})$ ε_v
1	■100 ■300 ■500	4.50 3.80 3.30	4.96 3.81 3.12	125	259.1	253.9	
2	■800	2.40	2.41	39	71.6	40.2	4334
3	■1800 ■2800	0.43 0.16	0.43 0.09	126	28.4	22.2	660.4

MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	R170
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	2.45 2.10 1.90	2.63 2.10 1.76	142	251.5	251.6	
2	■800	1.40	1.41	21	69.55	36.3	2545
3	■1800 ■2800	0.20 0.03	0.21 0.04	133	28.4	21.5	268.1

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MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	R170
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	4.30 3.90 3.75	4.25 3.89 3.64	207	542.3	383.4	
2	■800	3.10	3.10	36	217.7	122.0	4351
3	■1800 ■2800	0.68 0.25	0.68 0.14	136	91.3	69.0	851.9

MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	785
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	2.40 1.80 1.45	2.50 1.80 1.30	110	257.3	252.7	
2	■800	0.95	0.95	30.5	50.5	38.1	2114
3	■1800 ■2800	0.11 0.02	0.11 0.02	166	15.6	13.5	173.4

MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	785
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	2.70 2.20 1.90	2.80 2.20 1.80	142	359.1	315.3	
2	■800	1.30	1.30	35	77.8	54.0	2670
3	■1800 ■2800	0.18 0.05	0.18 0.037	160	25.7	21.7	277.9

MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	785
WHEEL LOAD	REAR, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	1.70 1.35 1.10	2.00 1.35 1.03	100	160.2	171.2	
2	■800	0.80	0.80	25	47.1	27.8	1600
3	■1800 ■2800	0.06 0.01	0.06 0.01	294	16.4	13.5	85.63

MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	785
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN (x10^{-3}) ε_v
1	■100 ■300 ■500	3.10 2.60 2.40	3.12 2.61 2.32	159	414.9	342.9	
2	■800	1.84	1.84	41	150.2	92.2	3062
3	■1800 ■2800	0.27 0.06	0.27 0.09	220	54.3	44.2	374.0

MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	HD460 WATER CAR
WHEEL LOAD	FRONT, EMPTY

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN $(x10^{-3})$ ε_v
1	■100 ■300 ■500	1.58 1.16 0.92	1.73 1.16 0.85	129	201.1	209.4	
2	■800	0.59	0.59	36	36.9	26.6	1349
3	■1800 ■2800	0.06 0.01	0.06 0.01	212	11.1	9.5	99.37

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MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	HD1600 M1
WHEEL LOAD	FRONT, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	5.00 4.60 4.20	5.15 4.61 4.17	147	481.1	358.9	
2	■800	3.30	3.30	20.5	122.1	75.3	5757
3	■1800 ■2800	0.54 0.12	0.57 0.12	85	46.2	35.7	791.9

MINE	NEW VAAL COLLIERY
SITE NUMBER	3
TRUCK TYPE	HD1600 M1
WHEEL LOAD	REAR, FULL

LAYER	MDD DEPTH (mm)	DEFLECTIONS: MDD MEASURED (mm)	DEFLECTIONS: ELSYM5A CALCULATED (mm)	EFFECTIVE ELASTIC MODULUS (MPa) E_{Eff}	SUM OF PRINCIPAL STRESSES (kPa) θ	DEVIATOR STRESS (kPa) σ_D	VERTICAL STRAIN ($x10^{-3}$) ε_v
1	■100 ■300 ■500	5.10 4.80 4.50	5.37 4.80 4.31	138	569.3	392.0	
2	■800	3.60	3.59	34	239.9	138.2	5389
3	■1800 ■2800	0.70 0.29	0.71 0.15	141	95.9	75.1	914.3

SAFETY FACTOR ESTIMATION - NEW VAAL COLLIERY

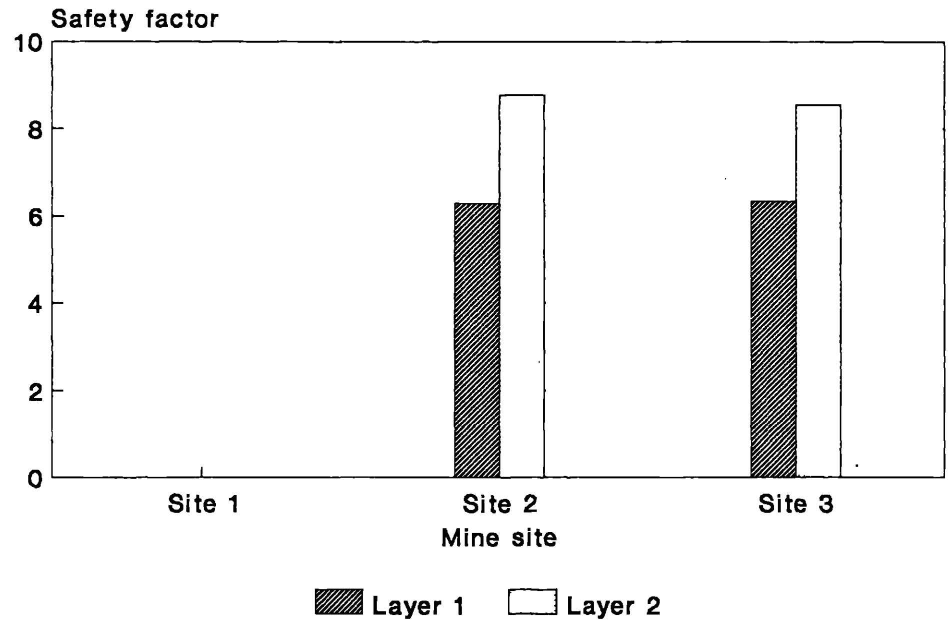
C-TERM = 223

Phi-TERM 5.5

Minor principle stress (kPa)		Site 1 layer 1	Site 1 layer 2	Site 2 layer 1	Site 2 layer 2	Site 3 layer 1	Site 3 layer 2
R170	FF			276	43	428	115
	FE			209	29	346	65
	RF			306	76	430	149
	RE			165	31	249	45
785	FF			181	21	329	62
	FE			125	14	254	40
	RF			214	53	359	108
	RE			78	15	165	33
Water car	FF			125	11		
	FE			95	9	206	30
	RF			174	52		
	RE			61	15		
HD1600	FF					399	90
	RF					444	166
Deviator stress (kPa)							
R170	FF			273	38	253	40
	FE			212	25	328	54
	RF			301	73	383	122
	RE			174	25	251	36

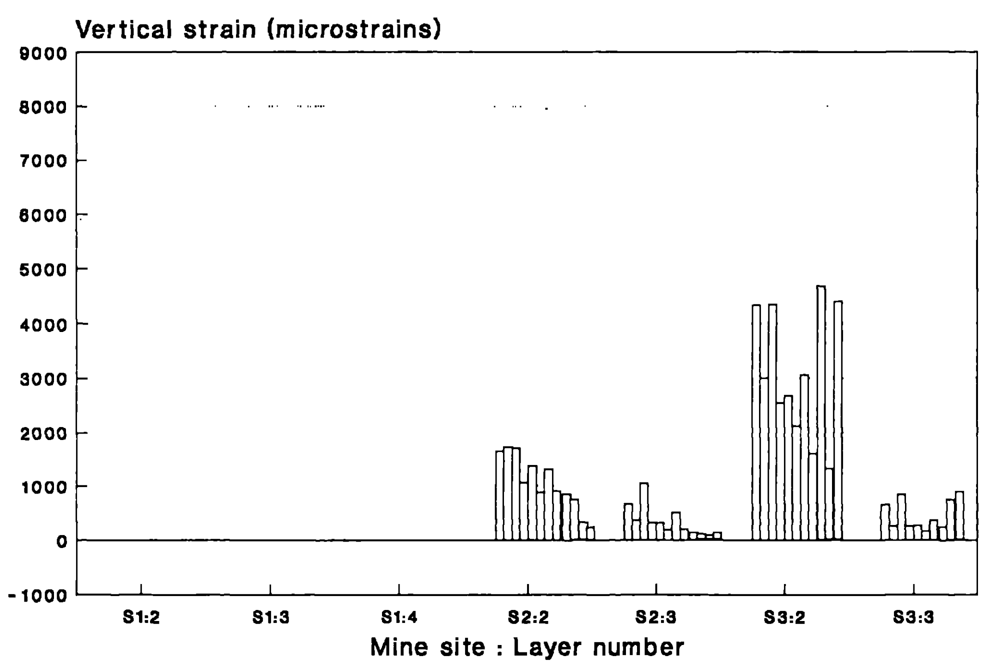
785	FF			188	17	315	54
	FE			132	11	252	38
	RF			219	50	342	92
	RE			83	13	171	27
Water car	FF			133	8		
	FE			101	7	209	26
	RF			165	49		
	RE			64	12		
HD1600	FF					359	75
	RF					392	138
Safety factor							
R170	FF			6.38	12.09	10.19	21.39
	FE			6.47	15.30	6.48	10.75
	RF			6.33	8.78	6.76	8.55
	RE			6.50	15.74	6.34	13.07
785	FF			6.48	19.91	6.45	10.44
	FE			6.90	27.27	6.43	11.66
	RF			6.39	10.29	6.43	8.88
	RE			7.86	23.50	6.61	14.98
Water car	FF			6.85	35.44		
	FE			7.38	38.93	6.49	14.92
	RF			7.15	10.39		
	RE			8.73	25.46		
HD1600	FF					6.73	9.57
	RF					6.80	8.23
Minimum safety factor				6.33	8.78	6.34	8.55

SAFETY FACTOR DESIGN CRITERIA
New Vaal Colliery all sites

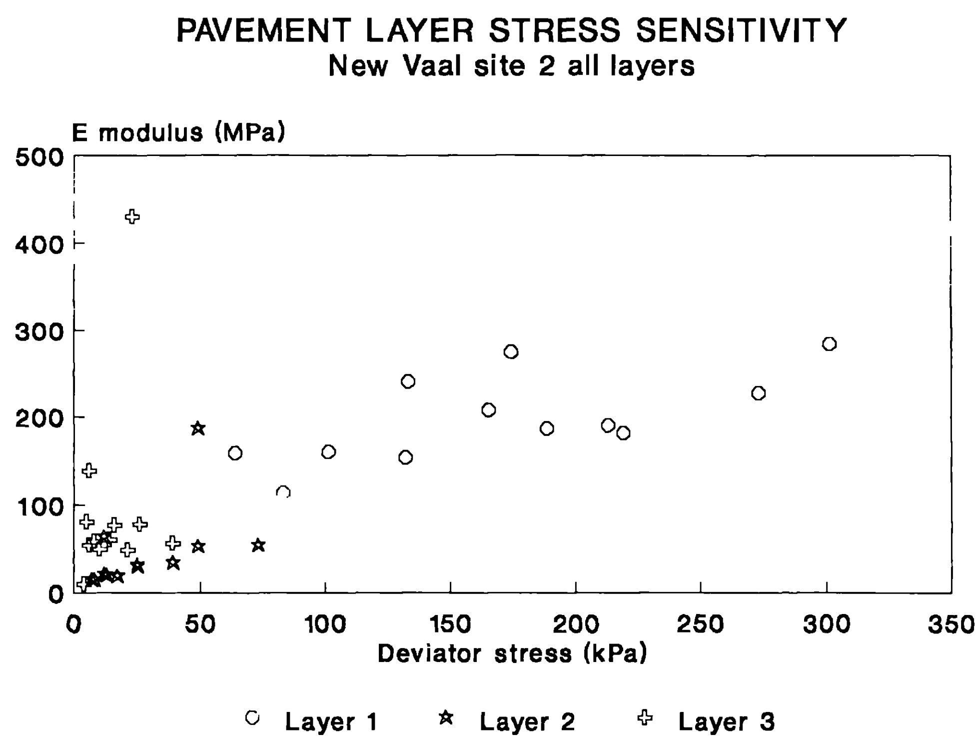


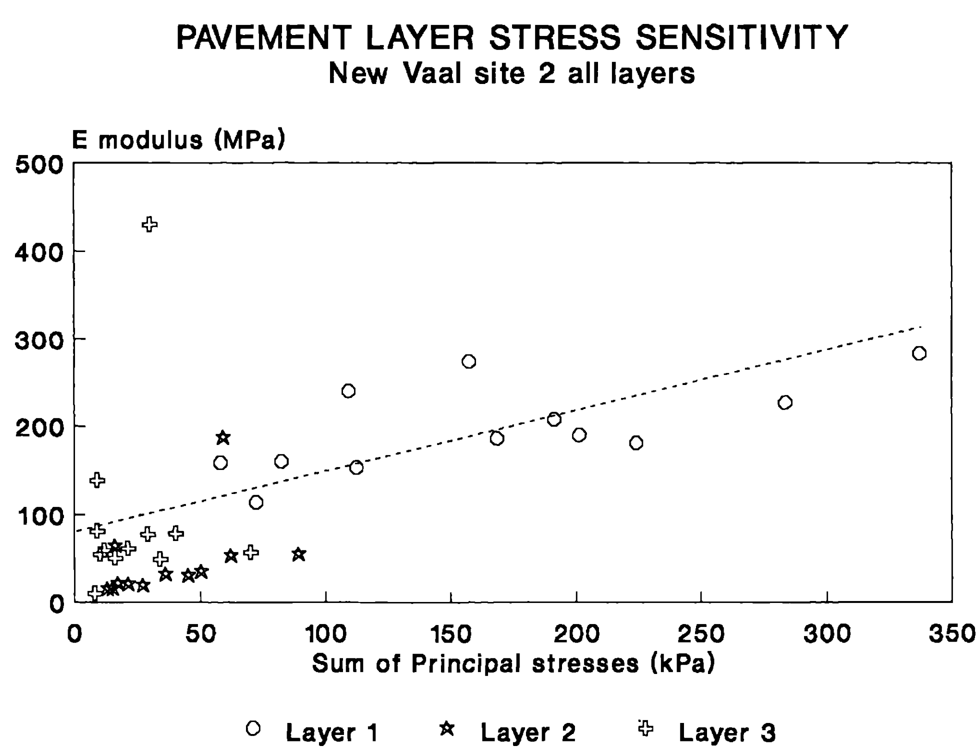
No data for site 1

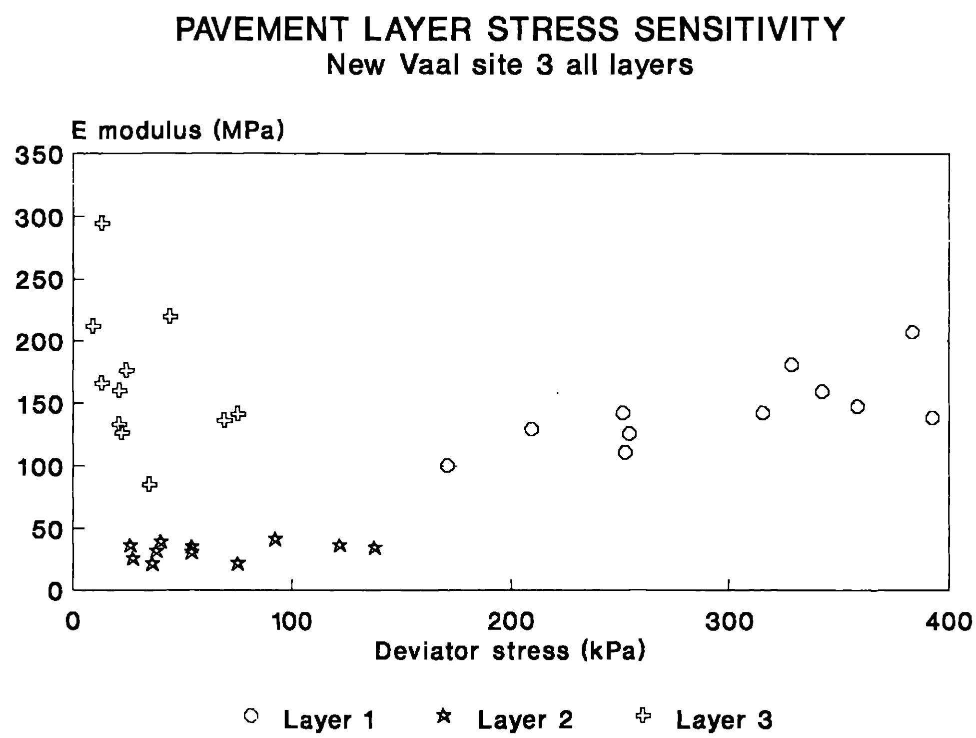
VERTICAL STRAIN DESIGN CRITERIA
New Vaal Colliery all three sites

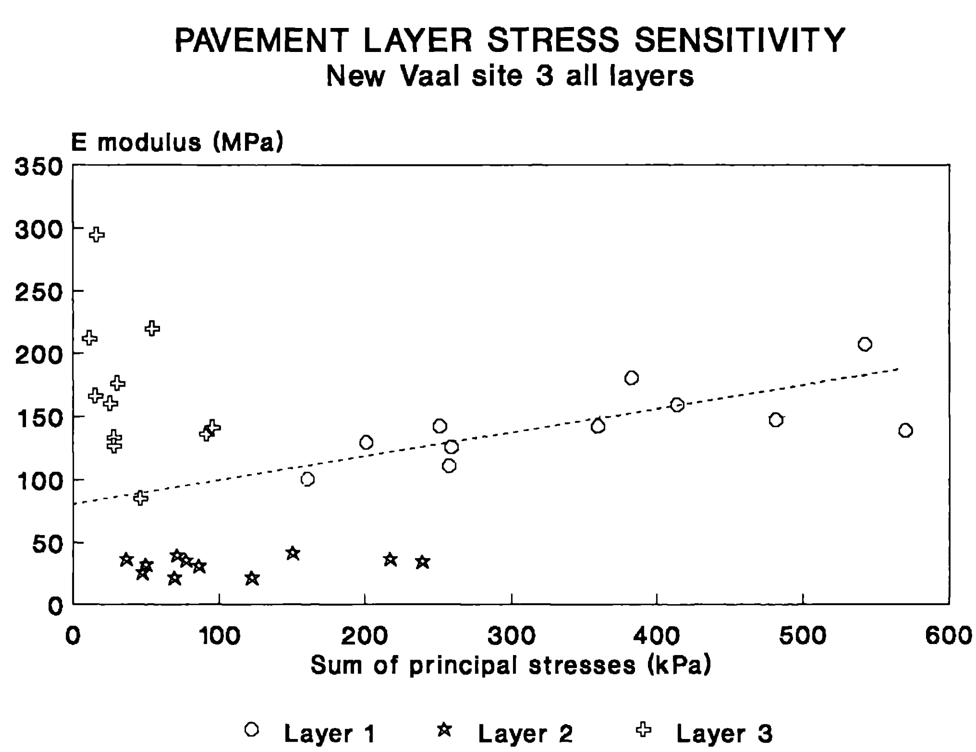


Site 1 no data


PAVEMENT LAYER STRESS SENSITIVITY
New Vaal site 2 all layers
E modulus (MPa)
500
400
300
200
100
0
0
50
100
150
200
250
300
350
Deviator stress (kPa)
Layer 1
Layer 2
Layer 3


PAVEMENT LAYER STRESS SENSITIVITY
New Vaal site 2 all layers
E modulus (MPa)
500
400
300
200
100
0
0
50
100
150
200
250
300
350
Sum of Principal stresses (kPa)
Layer 1
Layer 2
Layer 3


PAVEMENT LAYER STRESS SENSITIVITY
New Vaal site 3 all layers
E modulus (MPa)
350
300
250
200
150
100
50
0
0
100
200
300
400
Deviator stress (kPa)
Layer 1
Layer 2
Layer 3


PAVEMENT LAYER STRESS SENSITIVITY
New Vaal site 3 all layers
E modulus (MPa)
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
Sum of principal stresses (kPa)
Layer 1
Layer 2
Layer 3

APPENDIX D4

DATA PERTAINING TO THE PROPOSED EMPIRICAL RELATIONSHIP BETWEEN ELASTIC MODULUS AND DCP PENETRATION RATE

EMPIRICAL RELATIONSHIP BETWEEN EFFECTIVE ELASTIC MODULUS AND DCP PENETRATION RATE (DN)

KRIEL COLLIERY

	EFFECTIVE ELASTIC MODULUS SITE 1				EFFECTIVE ELASTIC MODULUS SITE 2				EFFECTIVE ELASTIC MODULUS SITE 3			
	layer 1	layer 2	layer 3	layer 4	layer 1	layer 2	layer 3	layer 4	layer 1	layer 2	layer 3	layer 4
	350	300	41	21	200	42	5000	33	500	2500	140	125
	200	200	50	20	100	35	3000	36	200	2500	160	250
	350	300	40	17	200	60	3000	20	600	2500	160	450
	380	380	41	19	120	30	3700	50	500	2500	130	450
	320	250	28	17	45	50	5000	25	250	2600	130	300
	550	450	35	19	55	50	4500	25	300	2400	230	400
	450	400	36	16	55	80	5000	25	600	2900	263	320
	550	500	55	14	160	58	4200	18				
	450	400	35	15								
	550	500	25	14								
Average Eeff (kPa)	415.00	368.00	38.60	17.20	116.88	50.63	4175.00	29.00	421.43	2557.14	173.29	327.86
Log avrg Eeff (kPa)	2.62	2.57	1.59	1.24	2.07	1.70	3.62	1.46	2.62	3.41	2.24	2.52
DN	1.38	4.75	8.10	4.65	3.35	1.90	1.38	2.30	2.67	0.47	1.39	7.50
Log DN	0.14	0.68	0.91	0.67	0.53	0.28	0.14	0.36	0.43	-0.33	0.14	0.88

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EMPIRICAL RELATIONSHIP BETWEEN EFFECTIVE ELASTIC MODULUS AND DCP PENETRATION RATE (DN)

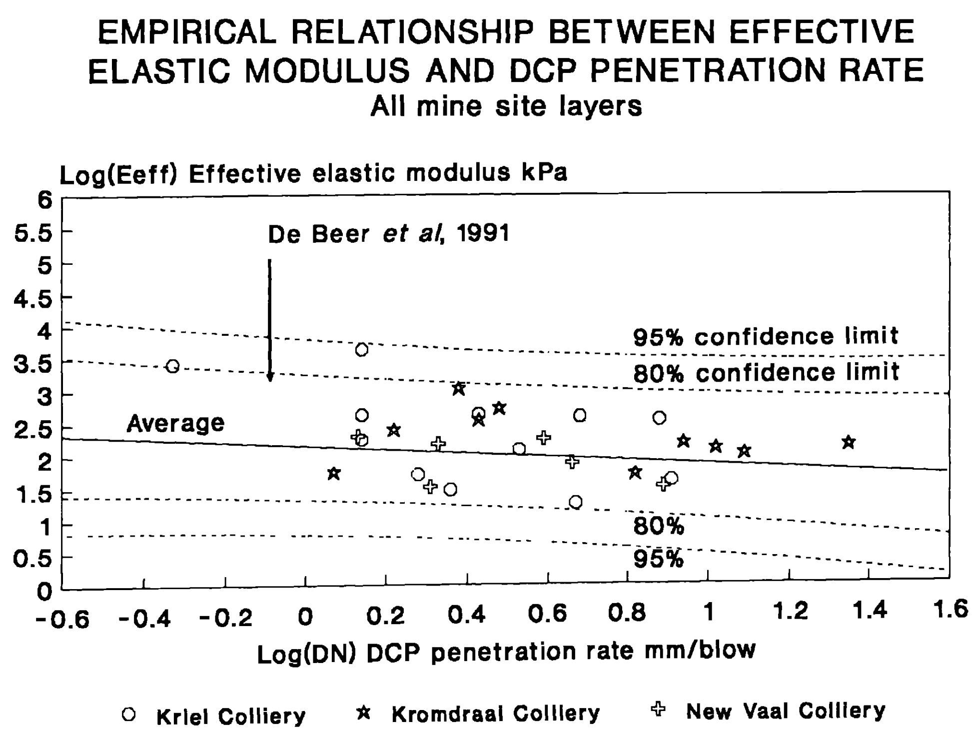
SACE KROMDRAAI COLLIERY

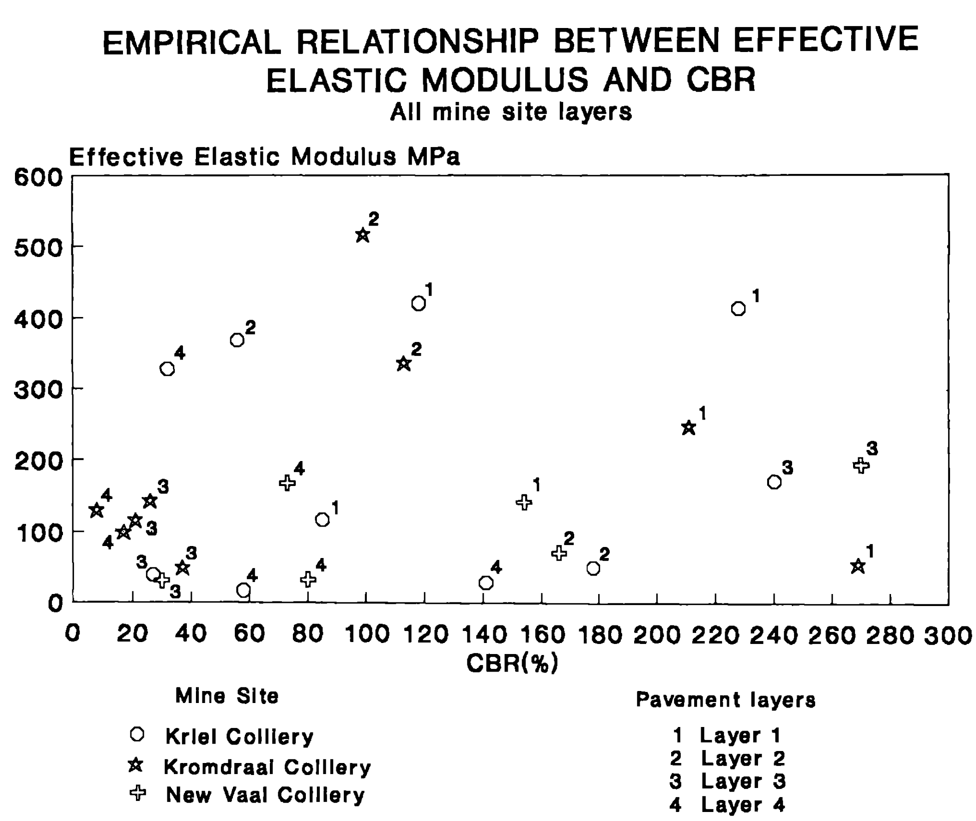
	EFFECTIVE ELASTIC MODULUS SITE 1				EFFECTIVE ELASTIC MODULUS SITE 2				EFFECTIVE ELASTIC MODULUS SITE 3			
	layer 1	layer 2	layer 3	layer 4	layer 1	layer 2	layer 3	layer 4	layer 1	layer 2	layer 3	
	180	1540	32	63		350	98	104	54	500	108	
	165	1490	40	93		310	97	158	52	460	153	
	240	750	84	146		338	137	110	55	395	156	
	350	620	68	106		342	220	97	61	834	123	
	160	1346	22	55		300	90	138	52	688	137	
	200	840	38	114		310	91	176	58	480	166	
	420	710	45	83		450	68	91	52	450	110	
	260	810	63	138		294	130	160	54	331	195	
Average Eeff (kPa)	246.88	1013.25	49.00	99.75		336.75	116.38	129.25	54.75	517.25	143.50	
Log avrg Eeff (kPa)	2.39	3.01	1.69	2.00		2.53	2.07	2.11	1.74	2.71	2.16	
DN	1.65	2.40	6.65	12.30		2.68	10.40	22.40	1.17	3.00	8.80	
Log DN	0.22	0.38	0.82	1.09		0.43	1.02	1.35	0.07	0.48	0.94	

EMPIRICAL RELATIONSHIP BETWEEN EFFECTIVE ELASTIC MODULUS AND DCP PENETRATION RATE (DN)

NEW VAAL COLLIERY

	EFFECTIVE ELASTIC MODULUS SITE 2			**EFFECTIVE ELASTIC MODULUS SITE 3**								
	layer 1	**layer 2**	**layer 3**	**layer 1**	**layer 2**	**layer 3**						
	240	15	81	125	39	126						
	160	15	100	180	30	176						
				207	36	136						
	158	64	138	142	21	133						
	227	34	48	142	35	160						
	190	31	61	110	30	166						
	283	54	56	159	41	220						
	274	30	77	100	25	294						
	186	19	50	129	36	212						
	153	21	54	147	20	85						
	181	53	78	138	34	141						
	113	20	58									
Average Eeff (kPa)	196.82	32.36	72.82	143.55	31.55	168.09						
Log avrg Eeff (kPa)	2.29	1.51	1.86	2.16	1.50	2.23						
DN	1.35	2.02	4.60	2.15	7.80	3.90						
Log DN	0.13	0.31	0.66	0.33	0.89	0.59						


EMPIRICAL RELATIONSHIP BETWEEN EFFECTIVE ELASTIC MODULUS AND DCP PENETRATION RATE
All mine site layers
Log(Eeff) Effective elastic modulus kPa
De Beer *et al*, 1991
95% confidence limit
80% confidence limit
Average
80%
95%
Log(DN) DCP penetration rate mm/blow
Kriel Colliery
Kromdraal Colliery
New Vaal Colliery


EMPIRICAL RELATIONSHIP BETWEEN EFFECTIVE ELASTIC MODULUS AND CBR
All mine site layers
Effective Elastic Modulus MPa
CBR(%)
Mine Site
Kriel Colliery
Kromdraal Colliery
New Vaal Colliery
Pavement layers
1 Layer 1
2 Layer 2
3 Layer 3
4 Layer 4

APPENDIX E1

KLEINKOPJE COLLIERY BLOCK 2A ROAD - CASE STUDY COMPARATIVE COST DATA

Contents

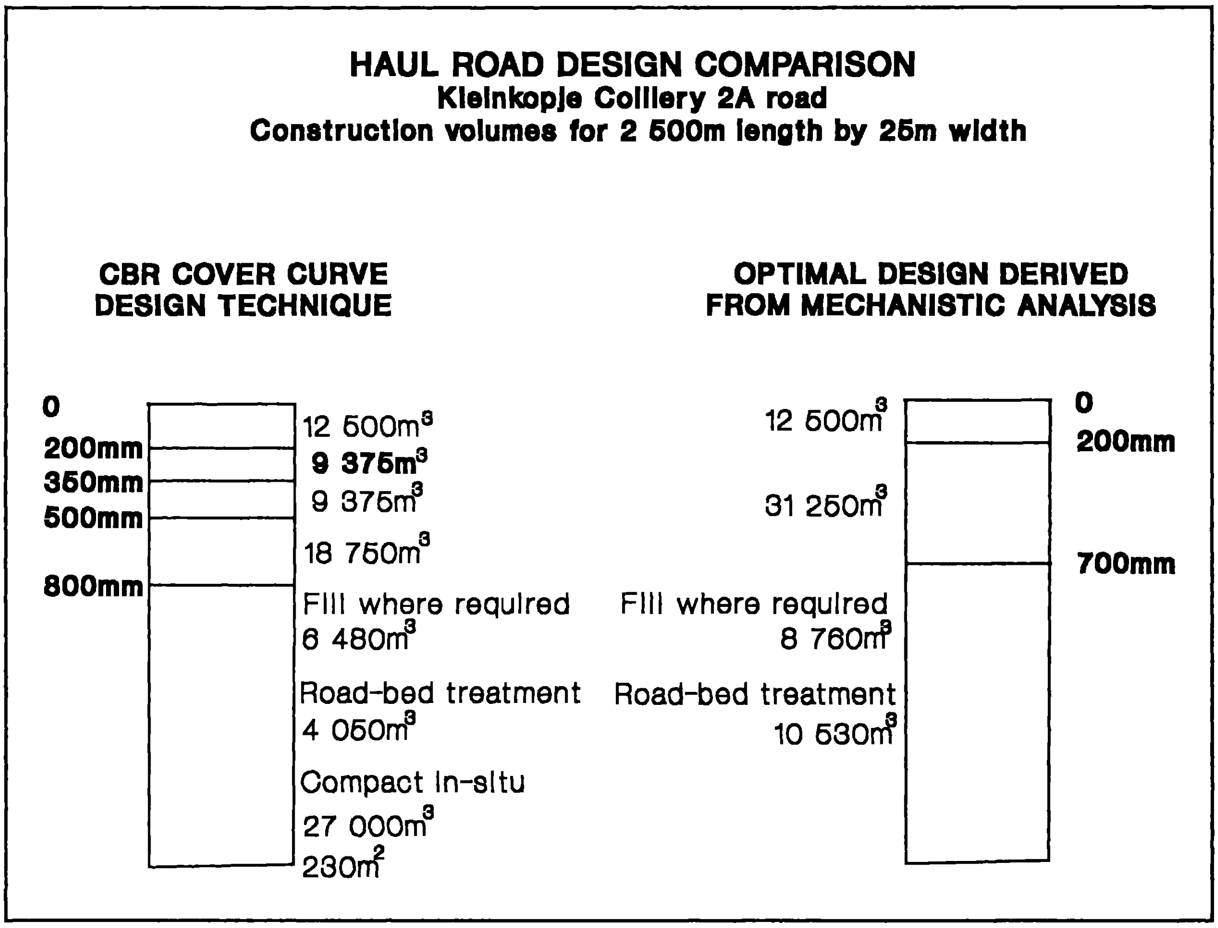


Figure E1 Summary of designs and construction volumes

Table E1 Unit Costs for Design Comparison

Activity description	Unit	Unit cost (R)
Compaction of in-situ	m^2 m^3	0,36 5,46
Road bed treatment to 90% Mod AASHTO Road bed treatment to 98% Mod AASHTO	m^3 m^3	2,09 2,21
Place and compact selected rock fill or layer	m^3	5,46
Place and compaction of wearing course	m^3	11,57
Construction of side drains	m^3	8,76
Construction of berms	m^3	7,49
Finishing	m	3,06

Table E2 Summary of preliminary and general costs - optimum mechanistic design

Item no.	Payment refers	Description	Unit	Quantity	Rate	Amount (R)
	SABS 1200A	**SCHEDULE 1: PRELIMINARY AND GENERAL**				
1.1 1.2 1.3	8.3	Fixed charge items Value-related items Time-related items			sum sum sum	
		TOTAL CARRIED TO SUMMARY				410 000

Table E3 Summary of costs for haulroad - optimal mechanistic design

Item no.	Payment refers	Description	Unit	Quantity	Rate	Amount (R)
	SABS 1200D	**SCHEDULE 2: HAUL ROAD**				
2.1	8.3	**EXCAVATION**				
1.2	8.3.3	Restricted excavation				
1.3						
	8.3.3(a)	Excavate in class A material and dispose for drains	m^3	1000	8,67	8670
	8.3.3(a)	Excavate in class A material and stockpile to form embankment Excavate in class A material side drain stockpile and form berms in 300mm layers	m^3	7500	7,49	56175
2.2	**SABS 1200DM** 8.3.3(a)	**EARTHWORKS, ROAD SUBGRADE**				
		Road bed preparation and compaction of materials to 90% Mod AASHTO density	m^3	10530	2,09	22008
	8.3.4(a)	Borrow to fill				
		Selected rock from spoils in 600mm layer where indicated and compacted by 10 passes of 10t vibratory roller. Blend and slush after compaction.	m^3	8760	5,46	47830
2.3	**SABS 1200ME** 8.3.4(a)	**BASE**				
		Selected rock from spoils				
		500mm layer, compacted by 10 passes of 10t vibratory roller. Blend and slush after compaction.	m^3	31250	5,46	170625
2.4	**SABS 1200MF** 8.3.1	**WEARING COURSE**				
		Selected ferricrete from designated borrow pit				
		200mm wearing course compacted to 98% Mod AASHTO	m^3	12500	11,57	144625
	8.4.13	**FINISHING**				
		Finishing of road reserve and unsurfaced road	m	2500	3,06	7650
		TOTAL CARRIED TO SUMMARY				457583

Table E4 Summary of costs - optimal mechanistic design

Item no.	Payment refers	Description		Amount (R)
1	SABS 1200A	SCHEDULE 1: PRELIMINARY AND GENERAL		410 000
2	SABS 1200D	SCHEDULE 2: HAUL ROADS		457 583
		VAT	@14%	121 461
TOTAL				989 044

Table E5 Summary of preliminary and general costs - CBR-based design

Item no.	Payment refers	Description	Unit	Quantity	Rate	Amount (R)
	SABS 1200A	SCHEDULE 1: PRELIMINARY AND GENERAL				
1.1 1.2 1.3	8.3	Fixed charge items Value-related items Time-related items			sum sum sum	
		TOTAL CARRIED TO SUMMARY				410 000

Table E6 Summary of haul road costs - CBR-based design

Item no.	Payment refers	Description	Unit	Quantity	Rate	Amount (R)
	SABS 1200D	**SCHEDULE 2: HAUL ROAD**				
2.1	8.3	**EXCAVATION**				
	8.3.3	Restricted excavation				
	8.3.3(a)	Excavate in class A material and dispose for drains	m^3	1000	8,67	8670
	8.3.3(a)	Excavate in class A material and stockpile to form embankment				
		Excavate in class A material side drain stockpile and form berms in 300mm layers	m^3	7500	7,49	56175
2.2	**SABS 1200DM**	**EARTHWORKS, ROAD SUBGRADE**				
		Compaction of in-situ	m^2	27000	0,36	9720
	8.3.3(a)		m^3	230	5,46	1256
		Road bed preparation and compaction of materials to 90% Mod AASHTO density	m^3	4050	2,09	8465
		Road bed preparation and compaction of materials to 90% Mod AASHTO density	m^3	6480	2,61	16 913
	8.3.4(a)	Borrow to fill Selected rock from spoils in 500mm layer where indicated and compacted by 10 passes of 10t vibratory roller. Blend and slush after compaction.	m^3	7300	5,46	39858
	8.3.4(a)	Borrow to rock layer Selected rock from spoils in 500mm layer where indicated and compacted by 10 passes of 10t vibratory roller. Blend and slush after compaction.	m^3	18750	5,46	102375
2.3	**SABS 1200ME**	**SUB-BASE**				
	8.3.4(a)	Selected ferricrete from designated borrow pit				
		150mm layer, compacted by 4 passes of 10t vibratory roller.	m^3	9375	5,46	108468
2.4	**SABS 1200ME**	**BASE**				
	8.3.4(a)	Selected ferricrete from designated borrow pit				
		150mm layer, compacted by 4 passes of 10t vibratory roller.	m^3	9375	5,46	108468
2.5	**SABS 1200MF**	**WEARING COURSE**				
	8.3.1	Selected ferricrete from designated borrow pit 200mm wearing course compacted to 98% Mod AASHTO	m^3	12500	11,57	144625
2.6	8.4.13	**FINISHING**				
		Finishing of road reserve and unsurfaced road	m	2500	3,06	7650
		TOTAL CARRIED TO SUMMARY				612643

Table E7 Summary of costs - CBR-based design

Item no.	Payment refers	Description		Amount (R)
1	SABS 1200A	SCHEDULE 1: PRELIMINARY AND GENERAL		410 000
2	SABS 1200D	SCHEDULE 2: HAUL ROADS		612 643
		VAT	@14%	143 169
TOTAL				1 165 812

APPENDIX F1

RESULTS OF FUNCTIONAL PERFORMANCE MONITORING - KRIEL COLLIERY

F1-2

Contents

FUNCTIONAL PERFORMANCE ASSESSMENT
KRIEL COLLIERY
Summary of defect (degree x extent) score

Site 1 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matrl.	Dust	Stones fixed	Stones loose	Cracks longtd.	Cracks slip	Cracks croc.	TOTAL DEFECT
May	9	6	8	4	6	9	4	6	12	8	72
June	4	4	9	12	8	9	12	1	4	3	66
July	9	6	9	6	9	8	9	2	4	6	68
August	6	6	9	12	16	6	6	1	4	6	72
September	9	4	6	12	9	6	4	1	4	9	64
October	16	4	12	12	6	6	6	1	6	25	94
November	9	4	9	12	12	6	9	1	4	9	75
December	4	2	4	16	16	6	9	1	2	2	62
January	9	4	9	8	16	6	9	1	4	12	78
February	6	4	9	12	16	6	6	2	4	1	66
March	2	1	3	20	25	6	6	1	2	1	67
April	4	4	9	16	20	6	6	1	4	1	71
Average dry season (May-Aug)	7.00	5.50	8.75	8.50	9.75	8.00	7.75	2.50	6.00	5.75	
Average wet season (Sept-Apr)	7.38	3.38	7.63	13.50	15.00	6.00	6.88	1.13	3.75	7.50	
Annual Average	7.25	4.08	8.00	11.83	13.25	6.67	7.17	1.58	4.50	6.92	

FUNCTIONAL PERFORMANCE ASSESSMENT
KRIEL COLLIERY
Summary of defect (degree x extent) score

Site 2 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matrl.	Dust	Stones fixed	Stones loose	Cracks longtd.	Cracks slip	Cracks croc.	TOTAL DEFECT
May	9	4	20	9	12	16	9	1	4	9	93
June	12	9	9	9	16	16	9	1	4	4	89
July	9	4	12	12	12	12	8	1	4	9	83
August	8	12	20	9	16	8	9	9	4	9	104
September	9	9	20	9	12	6	9	6	4	12	96
October	12	9	25	12	16	6	9	6	4	12	111
November	4	2	4	12	25	6	9	4	2	9	77
December	6	9	9	9	16	6	6	4	2	6	73
January	9	4	12	9	0	9	6	6	6	8	69
February	12	2	20	12	3	6	9	4	20	4	92
March	12	2	20	12	9	6	9	4	12	4	90
April	9	2	16	12	9	6	9	4	12	4	83
Average dry season (May-Aug)	9.50	7.25	15.25	9.75	14.00	13.00	8.75	3.00	4.00	7.75	
Average wet season (Sept-Apr)	9.13	4.88	15.75	10.88	11.25	6.38	8.25	4.75	7.75	7.38	
Annual Average	9.25	5.67	15.58	10.50	12.17	8.58	8.42	4.17	6.50	7.50	

FUNCTIONAL PERFORMANCE ASSESSMENT
KRIEL COLLIERY
Summary of defect (degree x extent) score

Site 3 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matrl.	Dust	Stones fixed	Stones loose	Cracks longtd.	Cracks slip	Cracks croc	TOTAL DEFECT
May	6	6	6	8	8	9	6	1	1	6	57
June	6	4	4	12	16	4	6	1	1	1	55
July	9	9	9	8	9	9	4	1	1	6	65
August	5	6	9	9	9	9	4	2	1	4	58
September	9	9	9	9	6	9	4	1	1	6	63
October	12	9	12	9	10	9	4	1	1	9	76
November	9	6	9	12	12	9	6	1	1	4	69
December	9	6	9	9	12	6	6	1	1	4	63
January	2	2	1	20	20	4	6	1	1	2	59
February	2	2	6	12	20	8	12	1	1	1	65
March	2	2	1	15	20	4	6	1	1	2	54
April	1	2	6	20	20	8	6	1	1	1	66
Average dry season (May-Aug)	6.50	6.25	7.00	9.25	10.50	7.75	5.00	1.25	1.00	4.25	
Average wet season (Sept-Apr)	5.75	4.75	6.63	13.25	15.00	7.13	6.25	1.00	1.00	3.63	
Annual Average	6.00	5.25	6.75	11.92	13.50	7.33	5.83	1.08	1.00	3.83	

FUNCTIONAL PERFORMANCE ASSESSMENT
KRIEL COLLIERY
Summary of maintenance, defect score and repetitions

Site 1

Month (1994-1995)	Days between maintenance	Defect (degree x extent)	Repetitions/day
March	0	67	136
December	1	62	98
September	2	64	82
February	3	66	137
July	3	68	114
April	4	71	98
November	4	75	101
June	5	66	114
May	6	72	113
August	7	75	107
January	9	78	113
October	9	94	94

FUNCTIONAL PERFORMANCE ASSESSMENT
KRIEL COLLIERY
Summary of maintenance, defect score and repetitions

Site 2

Month (1994-1995)	Days between maintenance	Defect (degree x extent)	Repetitions/day
January	0	75	50
December	1	73	34
July	2	83	49
November	3	77	37
February	4	92	64
March	6	90	54
September	6	96	29
May	9	93	31
October	11	111	48
April	12	83	61
June	15	89	58
August	15	112	50

FUNCTIONAL PERFORMANCE ASSESSMENT
KRIEL COLLIERY
Summary of maintenance, defect score and repetitions

Site 3

Month (1994-1995)	Days between maintenance	Defect (degree x extent)	Repetitions/day
January	0	59	113
April	0	66	98
February	1	65	137
March	2	54	136
May	2	57	113
December	3	63	98
June	4	55	114
November	5	69	101
August	6	59	107
October	8	76	94
July	11	65	114
September	13	63	82

Kriel Mine	**Site 1**	
Date of assessment	May 94	
Days since last maintenance	6	
Maintenance frequency/7 days	2	
Traffic (t/day)	16138.64	
Truck type(s)	R170, BD180	
Truck factor (t)	142.47	
Truck repetitions per day	113	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS. Watered recently, fine coal slush on road.		
WEARING COURSE SURFACE	Degree	Extent
Potholes	3	3
Corrugations	2	3
Rutting	4	2
Loose material	2	2
Dustiness	2	3
Stoniness - fixed	3	3
Stoniness - loose	2	2
Cracks - longitudinal	2	3
Cracks - slip	4	3
Cracks - crocodile	4	2
Sum Degree x extent		**72**
Skid resistance - wet	5	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 1**	
Date of assessment	Jun 94	
Days since last maintenance	5	
Maintenance frequency/7 days	2	
Traffic (t/day)	15910.45	
Truck type(s)	R170, BD180	
Truck factor (t)	139.12	
Truck repetitions per day	114	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS New WC addedd +50mm but stoney, poor crossfall.		
WEARING COURSE SURFACE	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose material	3	4
Dustiness	2	4
Stoniness - fixed	3	3
Stoniness - loose	3	4
Cracks - longitudional	1	1
Cracks - slip	2	2
Cracks - crocodile	1	3
Sum Degree x extent		**66**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudional	2	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 1**	
Date of assessment	Jul 94	
Days since last maintenance	3	
Maintenance frequency/7 days	3	
Traffic (t/day)	15910.45	
Truck type(s)	R170, BD180	
Truck factor (t)	139.12	
Truck repetitions per day	114	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS New WC firmer, better profile but defects increasing.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	3
Rutting	3	3
Loose material	3	2
Dustiness	3	3
Stoniness - fixed	2	4
Stoniness - loose	3	3
Cracks - longitudional	1	2
Cracks - slip	2	2
Cracks - crocodile	2	3
Sum Degree x extent		**68**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudional	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 1**	
Date of assessment	Aug 94	
Days since last maintenance	7	
Maintenance frequency/7 days	2	
Traffic (t/day)	17046.36	
Truck type(s)	R170, BD180	
Truck factor (t)	159.85	
Truck repetitions per day	107	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	3	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	3	2
Rutting	3	3
Loose material	4	3
Dustiness	4	4
Stoniness - fixed	3	2
Stoniness - loose	2	3
Cracks - longitudional	1	1
Cracks - slip	2	2
Cracks - crocodile	3	2
Sum Degree x extent		**75**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudional	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 1**	
Date of assessment	Sept 94	
Days since last maintenance	2	
Maintenance frequency/7 days	3	
Traffic (t/day)	11552.55	
Truck type(s)	R170, BD180	
Truck factor (t)	141.74	
Truck repetitions per day	82	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	17	
COMMENTS Bladed and loose material exc. Skid res dry poor.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	2	3
Loose material	4	3
Dustiness	3	3
Stoniness - fixed	3	2
Stoniness - loose	2	2
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	3	3
Sum Degree x extent		**64**
Skid resistance - wet	5	
Skid resistance - dry	5	
Erosion - longitudinal	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 1**	
Date of assessment	Oct 94	
Days since last maintenance	9	
Maintenance frequency/7 days	3	
Traffic (t/day)	12185.32	
Truck type(s)	R170, BD180	
Truck factor (t)	129.06	
Truck repetitions per day	94	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	65	
COMMENTS Severe croc cracks and large deformation/potholes.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	4	4
Corrugations	2	2
Rutting	3	4
Loose material	3	4
Dustiness	2	3
Stoniness - fixed	3	2
Stoniness - loose	3	2
Cracks - longitudinal	1	1
Cracks - slip	2	3
Cracks - crocodile	5	5
Sum Degree x extent		**94**
Skid resistance - wet	5	
Skid resistance - dry	5	
Erosion - longitudinal	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 1**	
Date of assessment	Nov 94	
Days since last maintenance	4	
Maintenance frequency/7 days	2	
Traffic (t/day)	13783.52	
Truck type(s)	R170, BD180	
Truck factor (t)	136.41	
Truck repetitions per day	101	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	66	
COMMENTS Muddy when wet, cracks as it dries.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	3	3
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	3	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	3	3
Sum Degree x extent		**75**
Skid resistance - wet	5	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 1**	
Date of assessment	Dec 94	
Days since last maintenance	1	
Maintenance frequency/7 days	2	
Traffic (t/day)	13479.13	
Truck type(s)	R170, BD180	
Truck factor (t)	138.03	
Truck repetitions per day	98	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	59	
COMMENTS Rain fairly recent, deforms in wheel tracks.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	1	2
Rutting	2	2
Loose material	4	4
Dustiness	4	4
Stoniness - fixed	3	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	2
Cracks - crocodile	1	2
Sum Degree x extent		**62**
Skid resistance - wet	4	
Skid resistance - dry	5	
Erosion - longitudinal	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 1**	
Date of assessment	Jan 95	
Days since last maintenance	9	
Maintenance frequency/7 days	3	
Traffic (t/day)	17393.48	
Truck type(s)	R170, BD180	
Truck factor (t)	154.84	
Truck repetitions per day	113	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	101	
COMMENTS Sl more dust (coal) loaded side of road.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	3	3
Loose material	2	4
Dustiness	4	4
Stoniness - fixed	3	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	4	3
Sum Degree x extent		**78**
Skid resistance - wet	4	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 1**	
Date of assessment	Feb 95	
Days since last maintenance	3	
Maintenance frequency/7 days	3	
Traffic (t/day)	18592.82	
Truck type(s)	R170, BD180	
Truck factor (t)	135.62	
Truck repetitions per day	137	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	45	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	3	3
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	3	2
Stoniness - loose	2	3
Cracks - longitudinal	1	2
Cracks - slip	2	2
Cracks - crocodile	1	1
Sum Degree x extent		**66**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

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Kriel Mine	**Site 1**	
Date of assessment	Mar 95	
Days since last maintenance	0	
Maintenance frequency/7 days	3	
Traffic (t/day)	17783.39	
Truck type(s)	R170, BD180	
Truck factor (t)	131.09	
Truck repetitions per day	136	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	141	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	1
Corrugations	1	1
Rutting	1	3
Loose material	4	5
Dustiness	5	5
Stoniness - fixed	3	2
Stoniness - loose	2	3
Cracks - longitudinal	1	1
Cracks - slip	2	1
Cracks - crocodile	1	1
Sum Degree x extent		67
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 1**	
Date of assessment	Apr 95	
Days since last maintenance	4	
Maintenance frequency/7 days	2	
Traffic (t/day)	16217.78	
Truck type(s)	R170, BD180	
Truck factor (t)	165.34	
Truck repetitions per day	98	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	64	
COMMENTS Less loose fine on faster unladen side.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose material	4	4
Dustiness	4	5
Stoniness - fixed	3	2
Stoniness - loose	2	3
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	1	1
Sum Degree x extent		**71**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudional	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 2**	
Date of assessment	May 94	
Days since last maintenance	9	
Maintenance frequency/7 days	1	
Traffic (t/day)	4399.45	
Truck type(s)	R170, BD180	
Truck factor (t)	142.5	
Truck repetitions per day	31	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	0	
COMMENTS 60mm WC placed, not scarified, stoney and dusty		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	4	5
Loose material	3	3
Dustiness	3	4
Stoniness - fixed	4	4
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	3	3
Sum Degree x extent		**93**
Skid resistance - wet	5	
Skid resistance - dry	3	
Erosion - longitudional	2	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

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Kriel Mine	**Site 2**	
Date of assessment	Jun 94	
Days since last maintenance	15	
Maintenance frequency/7 days	2	
Traffic (t/day)	8076.64	
Truck type(s)	R170, BD180	
Truck factor (t)	139.12	
Truck repetitions per day	58	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	0	
COMMENTS Poor skid res and erosion (l and a) and drainage.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	4
Corrugations	3	3
Rutting	3	3
Loose material	3	3
Dustiness	4	4
Stoniness - fixed	4	4
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	2	2
Sum Degree x extent		**89**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	3	
Drainage - side of road	3	

Kriel Mine	**Site 2**	
Date of assessment	Jul 94	
Days since last maintenance	2	
Maintenance frequency/7 days	1	
Traffic (t/day)	6774.55	
Truck type(s)	R170, BD180	
Truck factor (t)	139.12	
Truck repetitions per day	49	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS Dusty, loose material from blading, damage on bends exc.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	3	4
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	3	4
Stoniness - loose	2	4
Cracks - longitudional	1	1
Cracks - slip	2	2
Cracks - crocodile	3	3
Sum Degree x extent		**83**
Skid resistance - wet	5	
Skid resistance - dry	4	
Erosion - longitudional	2	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

Kriel Mine	**Site 2**	
Date of assessment	Aug 94	
Days since last maintenance	15	
Maintenance frequency/7 days	1	
Traffic (t/day)	8007.27	
Truck type(s)	R170, BD180	
Truck factor (t)	159.85	
Truck repetitions per day	50	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	3	
COMMENTS Longitudinal cracks appear, poor profile.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	4	4
Corrugations	4	3
Rutting	5	4
Loose material	3	3
Dustiness	4	4
Stoniness - fixed	2	4
Stoniness - loose	3	3
Cracks - longitudinal	3	3
Cracks - slip	2	2
Cracks - crocodile	3	3
Sum Degree x extent		**112**
Skid resistance - wet	4	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	4	
Drainage - side of road	4	

Kriel Mine	**Site 2**	
Date of assessment	Sep 94	
Days since last maintenance	6	
Maintenance frequency/7 days	2	
Traffic (t/day)	4084.95	
Truck type(s)	R170, BD180	
Truck factor (t)	141.74	
Truck repetitions per day	29	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	17	
COMMENTS Vlei dry but profile sstill poor. Some local repairs.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	3	3
Rutting	5	4
Loose material	3	3
Dustiness	4	3
Stoniness - fixed	2	3
Stoniness - loose	3	3
Cracks - longitudinal	2	3
Cracks - slip	2	2
Cracks - crocodile	4	3
Sum Degree x extent		**96**
Skid resistance - wet	5	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	4	

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Kriel Mine	**Site 2**	
Date of assessment	Oct 94	
Days since last maintenance	11	
Maintenance frequency/7 days	3	
Traffic (t/day)	6233.73	
Truck type(s)	R170, BD180	
Truck factor (t)	129.06	
Truck repetitions per day	48	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	65	
COMMENTS Road appears to be drying after vlei pumped.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	4
Corrugations	3	3
Rutting	5	5
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	2	3
Stoniness - loose	3	3
Cracks - longitudinal	2	3
Cracks - slip	2	2
Cracks - crocodile	4	3
Sum Degree x extent		**111**
Skid resistance - wet	5	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

Kriel Mine	**Site 2**	
Date of assessment	Nov 94	
Days since last maintenance	3	
Maintenance frequency/7 days	3	
Traffic (t/day)	4647.2	
Truck type(s)	R170, BD180	
Truck factor (t)	127.24	
Truck repetitions per day	37	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	66	
COMMENTS Recent blading, stones form ridges, potholes not out.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	1	2
Rutting	2	2
Loose material	3	4
Dustiness	5	5
Stoniness - fixed	2	3
Stoniness - loose	3	3
Cracks - longitudinal	2	2
Cracks - slip	1	2
Cracks - crocodile	3	3
Sum Degree x extent		**77**
Skid resistance - wet	5	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

Kriel Mine	**Site 2**	
Date of assessment	Dec 94	
Days since last maintenance	1	
Maintenance frequency/7 days	2	
Traffic (t/day)	4859.57	
Truck type(s)	R170, BD180	
Truck factor (t)	142.56	
Truck repetitions per day	34	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	59	
COMMENTS Some pushing thru of base seen, dusty despite water.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	3	3
Rutting	3	3
Loose material	3	3
Dustiness	4	4
Stoniness - fixed	2	3
Stoniness - loose	2	3
Cracks - longitudional	2	2
Cracks - slip	1	2
Cracks - crocodile	2	3
Sum Degree x extent		**73**
Skid resistance - wet	4	
Skid resistance - dry	4	
Erosion - longitudional	2	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

Kriel Mine	**Site 2**	
Date of assessment	Jan 95	
Days since last maintenance	0	
Maintenance frequency/7 days	1	
Traffic (t/day)	5807.52	
Truck type(s)	R170, BD180	
Truck factor (t)	116.86	
Truck repetitions per day	50	
Truck speed (km/h)	40	
Moisture conditions	Wet	
Rainfall for month (mm)	101	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	3	4
Loose material	3	3
Dustiness	2	3
Stoniness - fixed	3	3
Stoniness - loose	3	2
Cracks - longitudinal	2	3
Cracks - slip	2	3
Cracks - crocodile	2	4
Sum Degree x extent		**75**
Skid resistance - wet	5	
Skid resistance - dry	5	
Erosion - longitudinal	3	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

Kriel Mine	**Site 2**	
Date of assessment	Feb 95	
Days since last maintenance	4	
Maintenance frequency/7 days	2	
Traffic (t/day)	8201.00	
Truck type(s)	R170, BD180	
Truck factor (t)	136.47	
Truck repetitions per day	64	
Truck speed (km/h)	40	
Moisture conditions	Wet	
Rainfall for month (mm)	45	
COMMENTS Very badly cut up - rain. Worse than score predicts.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	4	3
Corrugations	1	2
Rutting	5	4
Loose material	3	4
Dustiness	1	3
Stoniness - fixed	2	3
Stoniness - loose	3	3
Cracks - longitudinal	2	2
Cracks - slip	4	5
Cracks - crocodile	2	2
Sum Degree x extent		**92**
Skid resistance - wet	5	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

Kriel Mine	**Site 2**	
Date of assessment	Mar 95	
Days since last maintenance	6	
Maintenance frequency/7 days	1	
Traffic (t/day)	6909.43	
Truck type(s)	R170, BD180	
Truck factor (t)	127.95	
Truck repetitions per day	54	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	141	
COMMENTS Sl more damage seen on loaded side (degree +0.5-1)		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	4	3
Corrugations	1	2
Rutting	5	4
Loose material	3	4
Dustiness	3	3
Stoniness - fixed	2	3
Stoniness - loose	3	3
Cracks - longitudinal	2	2
Cracks - slip	4	3
Cracks - crocodile	2	2
Sum Degree x extent		**90**
Skid resistance - wet	5	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

Kriel Mine	**Site 2**	
Date of assessment	Apr 95	
Days since last maintenance	12	
Maintenance frequency/7 days	1	
Traffic (t/day)	10037.57	
Truck type(s)	R170, BD180	
Truck factor (t)	165.73	
Truck repetitions per day	61	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	64	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	1	2
Rutting	4	4
Loose material	3	4
Dustiness	3	3
Stoniness - fixed	2	3
Stoniness - loose	3	3
Cracks - longitudinal	2	2
Cracks - slip	3	4
Cracks - crocodile	2	2
Sum Degree x extent		**83**
Skid resistance - wet	5	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

Kriel Mine	**Site 3**	
Date of assessment	May 94	
Days since last maintenance	2	
Maintenance frequency/7 days	4	
Traffic (t/day)	16138.64	
Truck type(s)	R170, BD180	
Truck factor (t)	142.47	
Truck repetitions per day	113	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS Blading forms layers 30mm thick which lift up off road.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	2
Corrugations	2	3
Rutting	2	3
Loose material	2	4
Dustiness	2	4
Stoniness - fixed	3	3
Stoniness - loose	2	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**57**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 3**	
Date of assessment	Jun 94	
Days since last maintenance	4	
Maintenance frequency/7 days	4	
Traffic (t/day)	15910.45	
Truck type(s)	R170, BD180	
Truck factor (t)	139.12	
Truck repetitions per day	114	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS New Wc added, dusty despite damp road.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	2	2
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	2	2
Stoniness - loose	3	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		**55**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 3**	
Date of assessment	Jul 94	
Days since last maintenance	11	
Maintenance frequency/7 days	3	
Traffic (t/day)	15910.45	
Truck type(s)	R170, BD180	
Truck factor (t)	139.12	
Truck repetitions per day	114	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	0	
COMMENTS Loose material at side and centre, more rutting laden.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	3	3
Rutting	3	3
Loose material	2	4
Dustiness	3	3
Stoniness - fixed	3	3
Stoniness - loose	2	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**65**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 3**	
Date of assessment	Aug 94	
Days since last maintenance	6	
Maintenance frequency/7 days	2	
Traffic (t/day)	17046.36	
Truck type(s)	R170, BD180	
Truck factor (t)	159.85	
Truck repetitions per day	107	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	3	
COMMENTS Small potholes appearing, 40mm diam 30mm deep at stones.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	2
Corrugations	2	3
Rutting	3	3
Loose material	3	3
Dustiness	3	3
Stoniness - fixed	3	3
Stoniness - loose	2	2
Cracks - longitudinal	2	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**59**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 3**	
Date of assessment	Sept 94	
Days since last maintenance	13	
Maintenance frequency/7 days	2	
Traffic (t/day)	11552.55	
Truck type(s)	R170, BD180	
Truck factor (t)	141.74	
Truck repetitions per day	82	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	17	
COMMENTS Needs mtce, defect degree increasing both sides.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	3	3
Rutting	3	3
Loose material	3	3
Dustiness	2	3
Stoniness - fixed	3	3
Stoniness - loose	2	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	3	2
Sum Degree x extent		**63**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 3**	
Date of assessment	Oct 94	
Days since last maintenance	8	
Maintenance frequency/7 days	3	
Traffic (t/day)	12185.32	
Truck type(s)	R170, BD180	
Truck factor (t)	129.06	
Truck repetitions per day	94	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	65	
COMMENTS Watered am, Wc lifting out of road in plates ±30mm		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	4
Corrugations	3	3
Rutting	3	4
Loose material	3	3
Dustiness	2	5
Stoniness - fixed	3	3
Stoniness - loose	2	2
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	3	3
Sum Degree x extent		**76**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 3**	
Date of assessment	Nov 94	
Days since last maintenance	5	
Maintenance frequency/7 days	4	
Traffic (t/day)	13783.53	
Truck type(s)	R170, BD180	
Truck factor (t)	136.41	
Truck repetitions per day	98	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	66	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	3
Rutting	3	3
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	3	3
Stoniness - loose	2	3
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**69**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

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Kriel Mine	**Site 3**	
Date of assessment	Dec 94	
Days since last maintenance	3	
Maintenance frequency/7 days	2	
Traffic (t/day)	13479.13	
Truck type(s)	R170, BD180	
Truck factor (t)	138.03	
Truck repetitions per day	98	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	59	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	3
Rutting	3	3
Loose material	3	3
Dustiness	3	4
Stoniness - fixed	2	3
Stoniness - loose	2	3
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**63**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 3**	
Date of assessment	Jan 95	
Days since last maintenance	0	
Maintenance frequency/7 days	3	
Traffic (t/day)	17393.48	
Truck type(s)	R170, BD180	
Truck factor (t)	154.84	
Truck repetitions per day	113	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	101	
COMMENTS Mtce today, bumps on stones, some loose, watering too.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	1
Corrugations	1	2
Rutting	1	1
Loose material	4	5
Dustiness	4	5
Stoniness - fixed	2	2
Stoniness - loose	3	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	2
Sum Degree x extent		**59**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 3**	
Date of assessment	Feb 95	
Days since last maintenance	1	
Maintenance frequency/7 days	3	
Traffic (t/day)	18592.82	
Truck type(s)	R170, BD180	
Truck factor (t)	135.62	
Truck repetitions per day	137	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	45	
COMMENTS Loose material and dusty after blading.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	1
Corrugations	1	2
Rutting	2	3
Loose material	3	4
Dustiness	4	5
Stoniness - fixed	2	4
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		**65**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 3**	
Date of assessment	Mar 95	
Days since last maintenance	2	
Maintenance frequency/7 days	1	
Traffic (t/day)	17783.39	
Truck type(s)	R170, BD180	
Truck factor (t)	131.09	
Truck repetitions per day	136	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	141	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	1
Corrugations	1	2
Rutting	1	1
Loose material	3	5
Dustiness	4	5
Stoniness - fixed	2	2
Stoniness - loose	3	2
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	1	2
Sum Degree x extent		**54**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kriel Mine	**Site 3**	
Date of assessment	Apr 95	
Days since last maintenance	0	
Maintenance frequency/7 days	1	
Traffic (t/day)	16217.78	
Truck type(s)	R170, BD180	
Truck factor (t)	165.34	
Truck repetitions per day	98	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	64	
COMMENTS Loose material and dusty out of wheel tracks.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	1	2
Rutting	2	3
Loose material	5	4
Dustiness	4	5
Stoniness - fixed	2	4
Stoniness - loose	2	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		**66**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	2	

APPENDIX F2

RESULTS OF FUNCTIONAL PERFORMANCE MONITORING - KROMDRAAI COLLIERY

F2-2

Contents

FUNCTIONAL PERFORMANCE ASSESSMENT
KROMDRAAI COLLIERY
Summary of defect (degree x extent) scores

SITE 1 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matr.	Dust	Stones fixed	Stones lse	Cracks longtd	Cracks slip	Cracks croc	TOTAL DEFECT
May	4	4	9	6	12	4	12	9	1	9	70
June	6	6	3	9	12	4	9	1	1	6	57
July	2	4	2	9	16	4	9	2	1	4	53
August	4	4	4	9	12	4	9	1	1	2	50
September	6	6	8	9	10	6	6	2	1	4	58
October	4	2	2	15	8	4	9	1	1	1	47
November	6	4	4	12	15	6	6	4	2	4	63
December	2	1	2	12	12	4	9	1	1	1	45
January	4	2	6	9	1	4	4	4	2	6	42
February	4	4	9	8	12	6	6	1	1	1	52
March	4	4	4	16	12	4	1	1	6	2	54
April	4	4	4	16	9	4	1	1	6	2	51
Average dry season (May-Aug)	4.00	4.50	4.50	8.25	13.00	4.00	9.75	3.25	1.00	5.25	
Average wet season (Sep-Apr)	4.25	3.38	4.88	12.13	9.88	4.75	5.25	1.88	2.50	2.63	
Annual average	4.17	3.75	4.75	10.83	10.92	4.50	6.75	2.33	2.00	3.50	

FUNCTIONAL PERFORMANCE ASSESSMENT
KROMDRAAI COLLIERY

Summary of defect (degree x extent) scores

SITE 2 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matrl.	Dust	Stones fixed	Stones loose	Cracks longtd	Cracks slip	Cracks croc	TOTAL DEFECT
May	1	4	4	12	15	4	12	1	1	8	62
June	3	4	4	6	20	4	12	1	1	2	57
July	4	4	4	9	16	4	9	1	1	6	58
August	2	1	4	16	20	4	12	1	1	6	67
September	1	4	6	9	16	4	9	1	1	6	57
October	1	4	6	6	16	4	6	1	1	6	51
November	1	4	6	12	20	4	9	1	1	6	64
December	1	4	6	12	16	4	9	1	1	4	58
January	1	4	6	9	0	4	9	1	1	4	39
February	1	4	6	9	1	4	6	1	1	4	37
March	4	4	6	9	16	4	6	2	1	4	56
April	4	4	6	9	12	4	9	1	1	4	54
Average dry season (May-Aug)	2.50	3.25	4.00	10.75	17.75	4.00	11.25	1.00	1.00	5.50	
Average wet season (Sep-Apr)	1.75	4.00	6.00	9.38	12.13	4.00	7.88	1.13	1.00	4.75	
Annual average	2.00	3.75	5.33	9.83	14.00	4.00	9.00	1.08	1.00	5.00	

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FUNCTIONAL PERFORMANCE ASSESSMENT
KROMDRAAI COLLIERY
Summary of defect (degree x extent) score

SITE 3 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matrl.	Dust	Stones fixed	Stones loose	Cracks longtd	Cracks slip	Cracks croc	TOTAL DEFECT
May	1	4	6	12	12	4	2	1	1	4	47
June	4	2	4	12	15	4	1	1	4	1	48
July	4	2	4	12	9	4	6	1	4	1	47
August	5	2	4	8	6	4	2	1	4	1	37
September	9	2	4	6	4	4	1	1	4	1	36
October	9	2	4	12	6	4	1	1	6	1	46
November	12	2	6	12	12	4	1	1	8	1	59
December	12	4	6	12	12	4	1	1	8	1	61
January	12	6	4	16	1	4	1	1	8	1	54
February	1	2	4	12	20	6	1	1	1	2	50
March	1	1	1	12	20	4	1	1	1	1	43
April	6	4	4	9	12	4	1	1	4	1	46
Average dry season (May-Aug)	3.50	2.50	4.50	11.00	10.50	4.00	2.75	1.00	3.25	1.75	
Average wet season (Sep-Apr)	7.75	2.88	4.13	11.38	10.88	4.25	1.00	1.00	5.00	1.13	
Annual average	6.33	2.75	4.25	11.25	10.75	4.17	1.58	1.00	4.42	1.33	

FUNCTIONAL PERFORMANCE ASSESSMENT
KROMDRAAI COLLIERY
Summary of maintenance, defect score and repetitions per month

Site 1

Month (1994-1995)	Days since last maintenance	Defect (degree x extent)	Repetitions per day
December	1	45	98
January	2	42	106
October	3	47	90
April	4	51	94
February	4	52	94
July	5	53	104
March	5	54	112
June	5	57	118
August	6	50	102
May	6	70	104
September	7	58	78
November	9	63	104

FUNCTIONAL PERFORMANCE ASSESSMENT
KROMDRAAI COLLIERY
Summary of maintenance, defect score and repetitions

Site 2

Month (1994-1995)	Days between maintenance	Defect (degree x extent)	Repetitions/day
December	1	58	56
February	2	37	47
October	4	51	49
March	5	56	47
January	6	51	45
April	6	54	53
July	8	58	52
September	11	57	39
June	12	57	59
August	12	66	51
May	14	62	54
November	14	64	52

FUNCTIONAL PERFORMANCE ASSESSMENT
KROMDRAAI COLLIERY
Summary of maintenance, defect score and repetitions

Site 3

Month (1994-1995)	Days between maintenance	Defect (degree x extent)	Repetitions/day
February	1	50	56
March	3	43	47
September	5	36	47
June	8	45	39
October	9	46	49
August	11	38	45
April	14	46	51
July	14	47	52
December	15	61	49
May	16	47	36
January	17	54	53
November	18	59	52

Kromdraai Mine	**Site 1**	
Date of assessment	May 94	
Days since last maintenance	6	
Maintenance frequency/7 days	2	
Traffic (t/day)	16000.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	108	
Truck speed (km/h)	35	
Moisture conditions	Dry	
Rainfall for month (mm)	0	
COMMENTS Cracking locally load side, loose material. Road bladed only and watered.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose material	2	3
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	3	4
Cracks - longitudional	3	3
Cracks - slip	1	1
Cracks - crocodile	3	3
Sum Degree x extent		**70**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	3	

Kromdraai Mine	**Site 1**	
Date of assessment	Jun 94	
Days since last maintenance	5	
Maintenance frequency/7 days	2	
Traffic (t/day)	17600.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	118	
Truck speed (km/h)	35	
Moisture conditions	Dry	
Rainfall for month (mm)	0	
COMMENTS Slightly more small potholes unloaded side (uphill)		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	2
Corrugations	2	3
Rutting	1	3
Loose material	3	3
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**57**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	3	
Drainage - side of road	1	

Kromdraai Mine	**Site 1**	
Date of assessment	Jul 94	
Days since last maintenance	5	
Maintenance frequency/7 days	1	
Traffic (t/day)	15400.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	104	
Truck speed (km/h)	35	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS Watered am. WC at edge of road - poor profile. Thickness WC 150mm		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	1
Corrugations	2	2
Rutting	1	2
Loose material	3	3
Dustiness	4	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	2
Cracks - crocodile	2	2
Sum Degree x extent		**53**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	3	
Drainage - side of road	3	

Kromdraai Mine	**Site 1**	
Date of assessment	Aug 94	
Days since last maintenance	6	
Maintenance frequency/7 days	2	
Traffic (t/day)	15200.00	
Truck type(s)	620E	
Truck factor (t)	148	
Truck repetitions per day	102	
Truck speed (km/h)	35	
Moisture conditions	dry	
Rainfall for month (mm)	0	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose material	3	3
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	1
Sum Degree x extent		**50**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	3	

Kromdraai Mine	**Site 1**	
Date of assessment	Sept 94	
Days since last maintenance	7	
Maintenance frequency/7 days	2	
Traffic (t/day)	11400.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	78	
Truck speed (km/h)	35	
Moisture conditions	dry	
Rainfall for month (mm)	8	
COMMENTS Road lifting up in plates 30mm thick, 200mm diameter. Layering of WC seen		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	2
Corrugations	2	3
Rutting	2	4
Loose material	3	3
Dustiness	2	5
Stoniness - fixed	2	3
Stoniness - loose	2	3
Cracks - longitudinal	2	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**58**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	3	

Kromdraai Mine	**Site 1**	
Date of assessment	Oct 94	
Days since last maintenance	3	
Maintenance frequency/7 days	1	
Traffic (t/day)	13200.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	90	
Truck speed (km/h)	35	
Moisture conditions	dry	
Rainfall for month (mm)	55	
COMMENTS Bladed recently, dusty with loose material on road. WC=150mm		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	2	1
Loose material	3	5
Dustiness	2	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		**47**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudional	1	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	3	

Kromdraai Mine	**Site 1**	
Date of assessment	Nov 94	
Days since last maintenance	9	
Maintenance frequency/7 days	2	
Traffic (t/day)	15400	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	104	
Truck speed (km/h)	35	
Moisture conditions	Moist	
Rainfall for month (mm)	68	
COMMENTS Shrinkage cracking seen. Some large local depressions locally.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose material	3	4
Dustiness	3	5
Stoniness - fixed	2	3
Stoniness - loose	2	3
Cracks - longitudional	2	2
Cracks - slip	1	2
Cracks - crocodile	2	2
Sum Degree x extent		**63**
Skid resistance - wet	5	
Skid resistance - dry	4	
Erosion - longitudional	2	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kromdraai Mine	**Site 1**	
Date of assessment	Dec 94	
Days since last maintenance	1	
Maintenance frequency/7 days	2	
Traffic (t/day)	14400	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	98	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	90	
COMMENTS Road pushing up in centre along longt cracks (load side only)		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	2
Corrugations	1	1
Rutting	2	1
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		**45**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	3	

Kromdraai Mine	**Site 1**	
Date of assessment	Jan 95	
Days since last maintenance	2	
Maintenance frequency/7 days	1	
Traffic (t/day)	15800	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	108	
Truck speed (km/h)	40	
Moisture conditions	Wet	
Rainfall for month (mm)	120	
COMMENTS Loose material in centre of road only. Unloaded side similar.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	1	2
Rutting	3	2
Loose material	3	3
Dustiness	1	1
Stoniness - fixed	2	2
Stoniness - loose	2	2
Cracks - longitudinal	2	2
Cracks - slip	1	2
Cracks - crocodile	3	2
Sum Degree x extent		**42**
Skid resistance - wet	1	
Skid resistance - dry	3	
Erosion - longitudinal	3	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

Kromdraai Mine	**Site 1**	
Date of assessment	Feb 95	
Days since last maintenance	4	
Maintenance frequency/7 days	1	
Traffic (t/day)	13800	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	88	
Truck speed (km/h)	40	
Moisture conditions	Wet	
Rainfall for month (mm)	49	
COMMENTS Slightly less dust on faster unloaded side.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose material	2	4
Dustiness	3	4
Stoniness - fixed	3	2
Stoniness - loose	2	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		**52**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	3	

Kromdraai Mine	**Site 1**	
Date of assessment	Mar 95	
Days since last maintenance	5	
Maintenance frequency/7 days	1	
Traffic (t/day)	16600.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	112	
Truck speed (km/h)	30	
Moisture conditions	dry	
Rainfall for month (mm)	128	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose material	4	4
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudional	1	1
Cracks - slip	2	3
Cracks - crocodile	1	2
Sum Degree x extent		**54**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	2	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	2	

Kromdraai Mine	**Site 1**	
Date of assessment	Apr 95	
Days since last maintenance	4	
Maintenance frequency/7 days	1	
Traffic (t/day)	13800.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	94	
Truck speed (km/h)	30	
Moisture conditions	moist	
Rainfall for month (mm)	114	
COMMENTS Slightly less rutting on unloaded side.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose material	4	4
Dustiness	3	3
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudinal	1	1
Cracks - slip	2	3
Cracks - crocodile	1	2
Sum Degree x extent		**51**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	2	

Kromdraai Mine	**Site 2**	
Date of assessment	May 94	
Days since last maintenance	14	
Maintenance frequency/7 days	1	
Traffic (t/day)	8000.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	54	
Truck speed (km/h)	30	
Moisture conditions	dry	
Rainfall for month (mm)	0	
COMMENTS Forming layers due to 20-30mm deep blading. Lifting loaded side.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	2
Loose material	3	4
Dustiness	3	5
Stoniness - fixed	2	2
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	4
Sum Degree x extent		**62**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	1	

Kromdraai Mine	**Site 2**	
Date of assessment	Jun 94	
Days since last maintenance	12	
Maintenance frequency/7 days	2	
Traffic (t/day)	8800.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	59	
Truck speed (km/h)	30	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS Considerable loose material, compacting on loaded side. Few large stones.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	3
Corrugations	2	2
Rutting	2	2
Loose material	3	2
Dustiness	4	5
Stoniness - fixed	2	2
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	2
Sum Degree x extent		**57**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	1	

Kromdraai Mine	**Site 2**	
Date of assessment	Jul 94	
Days since last maintenance	8	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	7700.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	52	
Truck speed (km/h)	30	
Moisture conditions	Dry	
Rainfall for month (mm)	0	
COMMENTS Croc cracks may be shrinkage. Rutting slightly less unloaded and less dust.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose material	3	3
Dustiness	4	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**58**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	1	

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Kromdraai Mine	**Site 2**	
Date of assessment	Aug 94	
Days since last maintenance	12	
Maintenance frequency/7 days	1	
Traffic (t/day)	7600.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	51	
Truck speed (km/h)	30	
Moisture conditions	dry	
Rainfall for month (mm)	0	
COMMENTS Less dust unloaded side (faster trucks - more blown to edge).		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	1	1
Rutting	2	2
Loose material	4	4
Dustiness	4	5
Stoniness - fixed	2	2
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**66**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	1	

Kromdraai Mine	**Site 2**	
Date of assessment	Sep 94	
Days since last maintenance	11	
Maintenance frequency/7 days	1	
Traffic (t/day)	5700.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	39	
Truck speed (km/h)	30	
Moisture conditions	dry	
Rainfall for month (mm)	8	
COMMENTS Poor cross erosion - too steep a profile (lateral).		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	3
Loose material	3	3
Dustiness	4	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**57**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	1	

Kromdraai Mine	**Site 2**	
Date of assessment	Oct 94	
Days since last maintenance	4	
Maintenance frequency/7 days	1	
Traffic (t/day)	6600.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	45	
Truck speed (km/h)	30	
Moisture conditions	dry	
Rainfall for month (mm)	55	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	3
Loose material	2	3
Dustiness	4	4
Stoniness - fixed	2	2
Stoniness - loose	3	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**51**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	1	

Kromdraai Mine	**Site 2**	
Date of assessment	Nov 94	
Days since last maintenance	14	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	7700	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	52	
Truck speed (km/h)	30	
Moisture conditions	Moist	
Rainfall for month (mm)	68	
COMMENTS Road edge cutting into road due to excessive cross erosion (both sides)		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	3
Loose material	3	4
Dustiness	4	5
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**64**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	1	

Kromdraai Mine	**Site 2**	
Date of assessment	Dec 94	
Days since last maintenance	1	
Maintenance frequency/7 days	1	
Traffic (t/day)	7200	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	49	
Truck speed (km/h)	30	
Moisture conditions	Dry	
Rainfall for month (mm)	90	
COMMENTS Layer WC added ±50mm. Rain 2 days previous eroded cross direction.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	3
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**58**
Skid resistance - wet	2	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	2	

Kromdraai Mine	**Site 2**	
Date of assessment	Jan 95	
Days since last maintenance	6	
Maintenance frequency/7 days	1	
Traffic (t/day)	7900	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	54	
Truck speed (km/h)	30	
Moisture conditions	Moist	
Rainfall for month (mm)	120	
COMMENTS Poor side drainage and cross erosion. Less rutting unloaded side.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	3
Loose material	3	3
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**51**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	3	

Kromdraai Mine	**Site 2**	
Date of assessment	Feb 95	
Days since last maintenance	2	
Maintenance frequency/7 days	1	
Traffic (t/day)	6900	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	44	
Truck speed (km/h)	30	
Moisture conditions	Wet	
Rainfall for month (mm)	49	
COMMENTS Slip cracks in middle pushing up centre of road - noticeable loaded side.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	3
Loose material	3	3
Dustiness	1	1
Stoniness - fixed	2	2
Stoniness - loose	3	2
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**37**
Skid resistance - wet	4	
Skid resistance - dry	2	
Erosion - longitudional	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	2	

Kromdraai Mine	**Site 2**	
Date of assessment	Mar 95	
Days since last maintenance	5	
Maintenance frequency/7 days	1	
Traffic (t/day)	8300	
Truck type(s)	630E	
Truck factor	148	
Truck repetitions per day	56	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	128	
COMMENTS Some pushing up in centre of road, lifts in plates 10mm- 15mm.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose material	3	3
Dustiness	4	4
Stoniness - fixed	2	2
Stoniness - loose	2	3
Cracks - longitudinal	1	2
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**56**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	3	

Kromdraai Mine	**Site 2**	
Date of assessment	Apr 95	
Days since last maintenance	6	
Maintenance frequency/7 days	1	
Traffic (t/day)	6900	
Truck type(s)	630E	
Truck factor	148	
Truck repetitions per day	47	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	114	
COMMENTS Slight potholes extra extent on unloaded side.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose material	3	3
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**54**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	1	
Erosion - cross	4	
Drainage - on road	3	
Drainage - side of road	3	

Kromdraai Mine	**Site 3**	
Date of assessment	May 94	
Days since last maintenance	16	
Maintenance frequency/7 days	0.2	
Traffic (t/day)	5400.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	36	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	0	
COMMENTS Traffic started. Forming hard layer in wheel path. Less dust unloaded.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	3
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	1	2
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**47**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudional	1	
Erosion - cross	3	
Drainage - on road	1	
Drainage - side of road	2	

Kromdraai Mine	**Site 3**	
Date of assessment	Jun 94	
Days since last maintenance	8	
Maintenance frequency/7 days	0.2	
Traffic (t/day)	7200.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	49	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	0	
COMMENTS Traffic increasing. signs of larger local deformation - both sides.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	2	1
Rutting	2	2
Loose material	3	4
Dustiness	3	5
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	1	1
Sum Degree x extent		**45**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	1	
Erosion - cross	3	
Drainage - on road	1	
Drainage - side of road	2	

Kromdraai Mine	**Site 3**	
Date of assessment	Jul 94	
Days since last maintenance	14	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	7700.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	52	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS Considerable loose material despite blading.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	2	2
Loose material	3	4
Dustiness	3	3
Stoniness - fixed	2	2
Stoniness - loose	3	2
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	1	1
Sum Degree x extent		**47**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	3	
Drainage - on road	1	
Drainage - side of road	2	

Kromdraai Mine	**Site 3**	
Date of assessment	Aug 94	
Days since last maintenance	11	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	7600.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	51	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	2	1
Rutting	2	2
Loose material	2	4
Dustiness	2	3
Stoniness - fixed	2	2
Stoniness - loose	2	1
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	1	1
Sum Degree x extent		**38**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	3	

Kromdraai Mine	**Site 3**	
Date of assessment	Sept 94	
Days since last maintenance	5	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	5700.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	39	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	8	
COMMENTS Deformation increasing - forming potholes - unloaded sl more.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	1
Rutting	2	2
Loose material	2	3
Dustiness	2	2
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	1	1
Sum Degree x extent		**36**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	3	

Kromdraai Mine	**Site 3**	
Date of assessment	Oct 94	
Days since last maintenance	9	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	6600.00	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	45	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	55	
COMMENTS Slip cracks visible, profile poor due to defm and worsening.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	2	1
Rutting	2	2
Loose material	3	4
Dustiness	2	3
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudinal	1	1
Cracks - slip	2	3
Cracks - crocodile	1	1
Sum Degree x extent		**46**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	3	

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Kromdraai Mine	**Site 3**	
Date of assessment	Nov 94	
Days since last maintenance	18	
Maintenance frequency/7 days	0.2	
Traffic (t/day)	7700	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	52	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	68	
COMMENTS Little mtce - potholes incr and loose material, dustier on loaded side.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	4	3
Corrugations	2	1
Rutting	2	3
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudional	1	1
Cracks - slip	2	4
Cracks - crocodile	1	1
Sum Degree x extent		**59**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	3	

Kromdraai Mine	**Site 3**	
Date of assessment	Dec 94	
Days since last maintenance	15	
Maintenance frequency/7 days	0.2	
Traffic (t/day)	7200	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	49	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	90	
COMMENTS Slip cracks in middle visible and some plating.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	4	3
Corrugations	2	2
Rutting	2	3
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudional	1	1
Cracks - slip	2	4
Cracks - crocodile	1	1
Sum Degree x extent		**61**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	3	

Kromdraai Mine	**Site 3**	
Date of assessment	Jan 95	
Days since last maintenance	17	
Maintenance frequency/7 days	0.3	
Traffic (t/day)	7900	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	54	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	120	
COMMENTS Very cut up after rain (bends), ponding and bad erosion across profile.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	4	3
Corrugations	3	2
Rutting	2	2
Loose material	4	4
Dustiness	1	1
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudinal	1	1
Cracks - slip	2	4
Cracks - crocodile	1	1
Sum Degree x extent		**54**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	3	

Kromdraai Mine	**Site 3**	
Date of assessment	Feb 95	
Days since last maintenance	1	
Maintenance frequency/7 days	1	
Traffic (t/day)	6900	
Truck type(s)	630E	
Truck factor (t)	148	
Truck repetitions per day	44	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	49	
COMMENTS More dust loaded side (spillage?), more rutting than unloaded.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	1	2
Rutting	2	2
Loose material	3	4
Dustiness	4	5
Stoniness - fixed	2	3
Stoniness - loose	1	1
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	2
Sum Degree x extent		**50**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	3	

Kromdraai Mine	**Site 3**	
Date of assessment	Mar 95	
Days since last maintenance	3	
Maintenance frequency/7 days	1	
Traffic (t/day)	8300	
Truck type(s)	630E	
Truck factor	148	
Truck repetitions per day	56	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	128	
COMMENTS Dusty with loose material, approx same both sides.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	1	1
Rutting	1	1
Loose material	3	4
Dustiness	4	5
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		43
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	3	
Drainage - on road	1	
Drainage - side of road	2	

Kromdraai Mine	**Site 3**	
Date of assessment	Apr 95	
Days since last maintenance	14	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	6900	
Truck type(s)	630E	
Truck factor	148	
Truck repetitions per day	47	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	114	
COMMENTS Profile not ideal, some erosion across road.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose material	3	3
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudinal	1	1
Cracks - slip	2	2
Cracks - crocodile	1	1
Sum Degree x extent		**46**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	3	

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APPENDIX F3

RESULTS OF FUNCTIONAL PERFORMANCE MONITORING - NEW VAAL COLLIERY

F3-2

Contents

FUNCTIONAL PERFORMANCE ASSESSMENT
NEW VAAL COLLIERY
Summary of defect (degree x extent) score

Site 1 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matrl.	Dust	Stones fixed	Stones loose	Cracks longtd	Cracks slip	Cracks croc.	TOTAL DEFECT
May	6	6	9	9	12	4	9	4	1	6	66
June	6	6	6	4	12	4	6	4	1	6	55
July	6	6	4	6	9	6	4	4	1	6	52
August	4	6	6	6	12	6	4	4	1	4	53
September	8	3	6	4	9	6	4	4	1	12	57
October	4	2	2	12	16	6	6	4	1	4	57
November	6	4	6	9	12	12	4	6	1	12	72
December	8	6	6	9	12	12	4	6	1	12	76
January	6	6	9	6	9	12	4	6	1	12	71
February	4	4	6	12	12	9	6	4	1	4	62
March	1	1	1	20	20	2	2	2	1	2	52
April	4	2	4	9	16	4	4	4	1	4	52
Average dry season (May-Aug)	5.50	6.00	6.25	6.25	11.25	5.00	5.75	4.00	1.00	5.50	
Average wet season (Sept-Apr)	5.13	3.50	5.00	10.13	13.25	7.88	4.25	4.50	1.00	7.75	
Annual average	5.25	4.33	5.42	8.83	12.58	6.92	4.75	4.33	1.00	7.00	

FUNCTIONAL PERFORMANCE ASSESSMENT
NEW VAAL COLLIERY
Summary of defect (degree x extent) score

Site 2 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matrl.	Dust	Stones fixed	Stones loose	Cracks longtd.	Cracks slip	Cracks croc.	TOTAL DEFECT
May	8	4	4	1	6	12	4	1	1	6	47
June	8	6	6	9	12	12	4	1	1	6	65
July	4	4	6	9	12	8	9	1	1	6	60
August	3	2	2	6	16	8	12	1	1	4	55
September	4	4	6	9	16	10	12	1	1	6	69
October	4	4	9	9	20	10	9	1	1	9	76
November	2	4	9	9	9	6	9	1	1	6	56
December	2	4	9	6	9	6	9	2	1	6	54
January	4	4	9	9	0	6	6	2	1	6	47
February	4	4	4	4	9	15	6	2	1	3	52
March	1	2	1	16	25	4	1	1	1	1	53
April	1	2	1	20	25	4	1	1	1	1	57
Average dry season (May-Aug)	5.75	4.00	4.50	6.25	11.50	10.00	7.25	1.00	1.00	5.50	
Average wet season (Sept-Apr)	2.75	3.50	6.00	10.25	14.13	7.63	6.63	1.38	1.00	4.75	
Annual average	3.75	3.67	5.50	8.92	13.25	8.42	6.83	1.25	1.00	5.00	

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FUNCTIONAL PERFORMANCE ASSESSMENT
NEW VAAL COLLIERY
Summary of defect (degree x extent) score

Site 3 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matrl.	Dust	Stones fixed	Stones loose	Cracks longtd.	Cracks slip	Cracks croc.	TOTAL DEFECT
May	4	9	4	12	20	16	6	1	1	4	77
June	9	9	9	12	16	16	6	1	1	4	83
July	9	9	4	12	16	16	6	1	1	4	78
August	5	9	9	12	20	12	12	1	1	6	87
September	6	9	6	12	16	8	12	1	1	6	77
October	6	9	4	20	20	8	12	1	1	4	85
November	3	8	8	20	20	10	4	1	3	6	83
December	3	4	4	20	20	8	4	1	3	6	73
January	2	2	2	20	20	8	4	1	3	6	68
February	2	6	4	16	16	12	9	1	2	6	74
March	4	6	4	12	20	16	6	1	1	4	74
April	4	9	4	12	20	16	6	1	1	6	79
Average dry season (May-Aug)	6.75	9.00	6.50	12.00	18.00	15.00	7.50	1.00	1.00	4.50	
Average wet season (Sept-Apr)	3.75	6.63	4.50	16.50	19.00	10.75	7.13	1.00	1.88	5.50	
Annual average	4.75	7.42	5.17	15.00	18.67	12.17	7.25	1.00	1.58	5.17	

FUNCTIONAL PERFORMANCE ASSESSMENT
NEW VAAL COLLIERY
Summary of maintenance, defect score and repetitions

Site 1

Month (1994-1995)	Days between maintenance	Defect (degree x extent)	Repetitions/day
October	1	57	360
March	2	52	348
June	2	55	356
April	3	52	372
July	3	52	334
August	4	53	345
September	5	57	361
February	5	62	364
January	7	71	388
November	7	72	353
May	8	66	393
December	12	76	356

FUNCTIONAL PERFORMANCE ASSESSMENT
NEW VAAL COLLIERY
Summary of maintenance, defect score and repetitions

Site 2

Month (1994-1995)	Days between maintenance	Defect (degree x extent)	Repetitions/day
March	1	53	184
April	1	57	177
February	3	52	133
May	4	47	186
December	5	54	169
January	6	56	187
November	8	56	168
July	11	60	179
June	13	65	131
August	16	54	199
September	16	69	195
October	18	76	161

FUNCTIONAL PERFORMANCE ASSESSMENT
NEW VAAL COLLIERY
Summary of maintenance, defect score and repetitions

Site 3

Month (1994-1995)	Days between maintenance	Defect (degree x extent)	Repetitions/day
January	2	68	66
December	3	73	45
February	7	74	104
March	8	74	68
April	11	79	72
May	14	77	77
June	17	78	82
September	18	77	91
July	18	78	117
October	19	85	25
November	21	83	100
August	21	88	106

New Vaal Mine	**Site 1**	
Date of assessment	May 94	
Days since last maintenance	8	
Maintenance frequency/7 days	3	
Traffic (t/day)	55000.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	393	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	0	
COMMENTS Loose material centre of road, polishing and pock marks seen.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	3	2
Rutting	3	3
Loose material	3	3
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	3	3
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**66**
Skid resistance - wet	2	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

New Vaal Mine	**Site 1**	
Date of assessment	Jun 94	
Days since last maintenance	2	
Maintenance frequency/7 days	3	
Traffic (t/day)	49800.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	356	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	0	
COMMENTS Pock marks form larger potholes.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	2	3
Rutting	2	3
Loose material	2	2
Dustiness	3	4
Stoniness - fixed	2	2
Stoniness - loose	2	3
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**55**
Skid resistance - wet	2	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

New Vaal Mine	**Site 1**	
Date of assessment	Jul 94	
Days since last maintenance	3	
Maintenance frequency/7 days	2	
Traffic (t/day)	46800.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	334	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	0	
COMMENTS Some croc cracks ±300mm edge side, centre of road loose material.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	2	3
Rutting	2	2
Loose material	3	2
Dustiness	3	3
Stoniness - fixed	2	3
Stoniness - loose	2	2
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**52**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

New Vaal Mine	**Site 1**	
Date of assessment	Aug 94	
Days since last maintenance	4	
Maintenance frequency/7 days	3	
Traffic (t/day)	48300.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	345	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	1	
COMMENTS Dry and dusty, not compacting well after scarify and blade.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	2	3
Loose material	3	2
Dustiness	3	4
Stoniness - fixed	2	3
Stoniness - loose	2	2
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**53**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

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New Vaal Mine	Site 1	
Date of assessment	Sept 94	
Days since last maintenance	5	
Maintenance frequency/7 days	3	
Traffic (t/day)	50500.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	361	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	0	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	4
Corrugations	1	3
Rutting	2	3
Loose material	2	2
Dustiness	3	3
Stoniness - fixed	2	3
Stoniness - loose	2	2
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	3	4
Sum Degree x extent		**57**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

New Vaal Mine	**Site 1**	
Date of assessment	Oct 94	
Days since last maintenance	1	
Maintenance frequency/7 days	4	
Traffic (t/day)	50398.26	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	360	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	37	
COMMENTS WC breaks out to a depth of 20-30mm in wheel tracks, poptholing worse.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	1	2
Rutting	1	2
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	2	3
Stoniness - loose	2	3
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**57**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

New Vaal Mine	**Site 1**	
Date of assessment	Nov 94	
Days since last maintenance	7	
Maintenance frequency/7 days	3	
Traffic (t/day)	49378.91	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	353	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	81	
COMMENTS Sl less loose material on unladen side of road.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	2	3
Loose material	3	3
Dustiness	4	3
Stoniness - fixed	3	4
Stoniness - loose	2	2
Cracks - longitudinal	2	3
Cracks - slip	1	1
Cracks - crocodile	3	4
Sum Degree x extent		**72**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

New Vaal Mine	**Site 1**	
Date of assessment	Dec 94	
Days since last maintenance	12	
Maintenance frequency/7 days	2	
Traffic (t/day)	49782.61	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	356	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	92	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	4
Corrugations	2	3
Rutting	2	3
Loose material	3	3
Dustiness	4	3
Stoniness - fixed	3	4
Stoniness - loose	2	2
Cracks - longitudinal	2	3
Cracks - slip	1	1
Cracks - crocodile	3	4
Sum Degree x extent		**76**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

New Vaal Mine	**Site 1**	
Date of assessment	Jan 95	
Days since last maintenance	7	
Maintenance frequency/7 days	1	
Traffic (t/day)	54347.83	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	388	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	109	
COMMENTS Bends genrally more damaged than straight sections, more cut when wet.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	2
Corrugations	2	3
Rutting	3	3
Loose material	2	3
Dustiness	3	3
Stoniness - fixed	3	4
Stoniness - loose	2	2
Cracks - longitudinal	2	3
Cracks - slip	1	1
Cracks - crocodile	3	4
Sum Degree x extent		**71**
Skid resistance - wet	4	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

New Vaal Mine	**Site 1**	
Date of assessment	Feb 95	
Days since last maintenance	5	
Maintenance frequency/7 days	2	
Traffic (t/day)	50928.55	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	364	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	43	
COMMENTS Dust palliative applied upto ramp 4.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugatic ns	2	2
Rutting	2	3
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	3	3
Stoniness - loose	2	3
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**62**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

New Vaal Mine	Site 1	
Date of assessment	Mar 95	
Days since last maintenance	2	
Maintenance frequency/7 days	3	
Traffic (t/day)	48720.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	348	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	87	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	1	1
Rutting	1	1
Loose material	4	5
Dustiness	4	5
Stoniness - fixed	1	2
Stoniness - loose	2	1
Cracks - longitudinal	1	2
Cracks - slip	1	1
Cracks - crocodile	1	2
Sum Degree x extent		**52**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

New Vaal Mine	**Site 1**	
Date of assessment	Apr 95	
Days since last maintenance	3	
Maintenance frequency/7 days	2	
Traffic (t/day)	52080.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	372	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	54	
COMMENTS Spillage on laden side increases dust, not only from WC.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	2	2
Loose material	3	3
Dustiness	4	4
Stoniness - fixed	2	2
Stoniness - loose	2	2
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**52**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

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New Vaal Mine	**Site 2**	
Date of assessment	May 94	
Days since last maintenance	4	
Maintenance frequency/7 days	1	
Traffic (t/day)	26000.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	186	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	0	
COMMENTS Small pock marks, local undulations 10-15mm, some large stones in wc		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	4
Corrugations	2	2
Rutting	2	2
Loose material	1	1
Dustiness	2	3
Stoniness - fixed	3	4
Stoniness - loose	2	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**47**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	3	

New Vaal Mine	**Site 2**	
Date of assessment	Jun 94	
Days since last maintenance	13	
Maintenance frequency/7 days	1	
Traffic (t/day)	18300.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	131	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	0	
COMMENTS Pock marks lead to potholes. Less dust unladen side. Crossfall excsve.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	4
Corrugations	2	3
Rutting	2	3
Loose material	3	3
Dustiness	3	4
Stoniness - fixed	3	4
Stoniness - loose	2	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**65**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	3	
Drainage - side of road	2	

New Vaal Mine	**Site 2**	
Date of assessment	Jul 94	
Days since last maintenance	11	
Maintenance frequency/7 days	1	
Traffic (t/day)	25000.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	179	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	0	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose material	3	3
Dustiness	3	4
Stoniness - fixed	4	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	3	2
Sum Degree x extent		**60**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	3	
Drainage - side of road	2	

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New Vaal Mine	**Site 2**	
Date of assessment	Aug 94	
Days since last maintenance	16	
Maintenance frequency/7 days	1	
Traffic (t/day)	27800.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	199	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	1	
COMMENTS Some polishing of WC evident, dusty laden side, more loose on road.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	2
Corrugations	2	1
Rutting	1	2
Loose material	3	2
Dustiness	4	4
Stoniness - fixed	4	2
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**54**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	3	
Drainage - side of road	2	

New Vaal Mine	**Site 2**	
Date of assessment	Sep 94	
Days since last maintenance	16	
Maintenance frequency/7 days	1	
Traffic (t/day)	27300.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	195	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	0	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose material	3	3
Dustiness	4	4
Stoniness - fixed	5	2
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	3	2
Sum Degree x extent		**69**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	3	
Drainage - side of road	2	

New Vaal Mine	**Site 2**	
Date of assessment	Oct 94	
Days since last maintenance	18	
Maintenance frequency/7 days	1	
Traffic (t/day)	22545.22	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	161	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	37	
COMMENTS Considerable loose mat and dusty, mostly small unladen, fine dust laden.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose material	3	3
Dustiness	4	5
Stoniness - fixed	5	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	3	3
Sum Degree x extent		**76**
Skid resistance - wet	4	
Skid resistance - dry	2	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	3	
Drainage - side of road	2	

New Vaal Mine	**Site 2**	
Date of assessment	Nov 94	
Days since last maintenance	8	
Maintenance frequency/7 days	1	
Traffic (t/day)	23568.26	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	168	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	81	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	2
Corrugations	2	2
Rutting	3	3
Loose material	3	3
Dustiness	3	3
Stoniness - fixed	3	2
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**56**
Skid resistance - wet	4	
Skid resistance - dry	2	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	2	

New Vaal Mine	**Site 2**	
Date of assessment	Dec 94	
Days since last maintenance	5	
Maintenance frequency/7 days	1	
Traffic (t/day)	23596.78	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	169	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	92	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	2
Corrugations	2	2
Rutting	3	3
Loose material	3	2
Dustiness	3	3
Stoniness - fixed	3	2
Stoniness - loose	3	3
Cracks - longitudinal	1	2
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**54**
Skid resistance - wet	4	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

New Vaal Mine	**Site 2**	
Date of assessment	Jan 95	
Days since last maintenance	6	
Maintenance frequency/7 days	1	
Traffic (t/day)	26197.83	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	187	
Truck speed	40	
Moisture conditions	Wet	
Rainfall for month	109	
COMMENTS Slippery when wet, cuts up on bends junctions easily. Little erosion.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose material	3	3
Dustiness	3	3
Stoniness - fixed	3	2
Stoniness - loose	2	3
Cracks - longitudinal	1	2
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**56**
Skid resistance - wet	5	
Skid resistance - dry	5	
Erosion - longitudinal	3	
Erosion - cross	4	
Drainage - on road	4	
Drainage - side of road	5	

New Vaal Mine	**Site 2**	
Date of assessment	Feb 95	
Days since last maintenance	3	
Maintenance frequency/7 days	2	
Traffic (t/day)	18665.64	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	133	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	43	
COMMENTS Loose material loaded side - poor skid resistance on exc crossfall.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose material	2	2
Dustiness	3	3
Stoniness - fixed	5	3
Stoniness - loose	3	2
Cracks - longitudinal	2	1
Cracks - slip	1	1
Cracks - crocodile	1	3
Sum Degree x extent		**52**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	3	
Drainage - side of road	2	

New Vaal Mine	**Site 2**	
Date of assessment	Mar 95	
Days since last maintenance	1	
Maintenance frequency/7 days	2	
Traffic (t/day)	257650.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	184	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	87	
COMMENTS Good after blading, loose and dust problem both sides		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	1	2
Rutting	1	1
Loose material	4	4
Dustiness	5	5
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		**53**
Skid resistance - wet	3	
Skid resistance - dry	2	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	2	

New Vaal Mine	**Site 2**	
Date of assessment	Apr 95	
Days since last maintenance	1	
Maintenance frequency/7 days	2	
Traffic (t/day)	24780.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	177	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	54	
COMMENTS Dusty and loose material after blading. Ridges from large stones in WC		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	1	2
Rutting	1	1
Loose material	4	5
Dustiness	5	5
Stoniness - fixed	2	2
Stoniness - loose	1	1
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		**57**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	2	
Erosion - cross	3	
Drainage - on road	2	
Drainage - side of road	2	

New Vaal Mine	**Site 3**	
Date of assessment	May 94	
Days since last maintenance	14	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	10800.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	77	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	0	
COMMENTS Less traffic - less mtce and water - dust appears to be ash component.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	3	3
Rutting	2	2
Loose material	3	4
Dustiness	4	5
Stoniness - fixed	4	4
Stoniness - loose	3	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**77**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	3	

New Vaal Mine	**Site 3**	
Date of assessment	Jun 94	
Days since last maintenance	17	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	11500.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	82	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	0	
COMMENTS Little difference laden/unladen sides, v dusty and loose material		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	3	3
Rutting	3	3
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	4	4
Stoniness - loose	3	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**78**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

New Vaal Mine	**Site 3**	
Date of assessment	Jul 94	
Days since last maintenance	18	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	16400.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	117	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	0	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	3
Corrugations	3	3
Rutting	2	2
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	4	4
Stoniness - loose	3	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**78**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

New Vaal Mine	**Site 3**	
Date of assessment	Aug 94	
Days since last maintenance	21	
Maintenance frequency/7 days	0.25	
Traffic (t/day)	14800.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	106	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	1	
COMMENTS Dry and dusty, little mtce, little traffic.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	3	3
Rutting	3	3
Loose material	3	4
Dustiness	4	5
Stoniness - fixed	4	3
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**88**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

New Vaal Mine	**Site 3**	
Date of assessment	Sept 94	
Days since last maintenance	18	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	12700.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	91	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	0	
COMMENTS Potholes and cracking evident under loose material. Skid res dry poor.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	3	3
Rutting	2	3
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	2	4
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**77**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

New Vaal Mine	**Site 3**	
Date of assessment	Oct 94	
Days since last maintenance	19	
Maintenance frequency/7 days	0.25	
Traffic (t/day)	3455.04	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	25	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	37	
COMMENTS More damage at junctions and turns, rutting and kicking out WC		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	3	3
Rutting	2	2
Loose material	4	5
Dustiness	4	5
Stoniness - fixed	2	4
Stoniness - loose	4	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**85**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

New Vaal Mine	**Site 3**	
Date of assessment	Nov 94	
Days since last maintenance	21	
Maintenance frequency/7 days	0.25	
Traffic (t/day)	14003.04	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	100	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	81	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	3
Corrugations	2	4
Rutting	2	4
Loose material	4	5
Dustiness	4	5
Stoniness - fixed	2	5
Stoniness - loose	4	1
Cracks - longitudional	1	1
Cracks - slip	1	3
Cracks - crocodile	2	3
Sum Degree x extent		**83**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

New Vaal Mine	**Site 3**	
Date of assessment	Dec 94	
Days since last maintenance	3	
Maintenance frequency/7 days	0.2	
Traffic (t/day)	6339.96	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	45	
Truck speed	40	
Moisture conditions	dry	
Rainfall for month	92	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	3
Corrugations	2	2
Rutting	2	2
Loose material	4	5
Dustiness	4	5
Stoniness - fixed	2	4
Stoniness - loose	4	1
Cracks - longitudional	1	1
Cracks - slip	1	3
Cracks - crocodile	2	3
Sum Degree x extent		**73**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

New Vaal Mine	**Site 3**	
Date of assessment	Jan 95	
Days since last maintenance	2	
Maintenance frequency/7 days	0.20	
Traffic (t/day)	9217.39	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	66	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	109	
COMMENTS Dust and loose material after blading. Ridges from fixed stones.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	2
Corrugations	1	2
Rutting	1	2
Loose material	4	5
Dustiness	4	5
Stoniness - fixed	2	4
Stoniness - loose	4	1
Cracks - longitudinal	1	1
Cracks - slip	1	3
Cracks - crocodile	2	3
Sum Degree x extent		**68**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	2	

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New Vaal Mine	Site 3	
Date of assessment	Feb 95	
Days since last maintenance	7	
Maintenance frequency/7 days	1	
Traffic (t/day)	14497.50	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	104	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	43	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	2
Corrugations	2	3
Rutting	2	2
Loose material	4	4
Dustiness	4	4
Stoniness - fixed	3	4
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	2
Cracks - crocodile	2	3
Sum Degree x extent		**74**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

New Vaal Mine	**Site 3**	
Date of assessment	Mar 95	
Days since last maintenance	8	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	9520.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	68	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	87	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	3	2
Rutting	2	2
Loose material	3	4
Dustiness	4	5
Stoniness - fixed	4	4
Stoniness - loose	3	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**74**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

New Vaal Mine	**Site 3**	
Date of assessment	Apr 95	
Days since last maintenance	11	
Maintenance frequency/7 days	0.5	
Traffic (t/day)	10080.00	
Truck type(s)	R170, 630E	
Truck factor	140	
Truck repetitions per day	72	
Truck speed	40	
Moisture conditions	Moist	
Rainfall for month	54	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	3	3
Rutting	2	2
Loose material	3	4
Dustiness	4	5
Stoniness - fixed	4	4
Stoniness - loose	3	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**79**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

F4-1

APPENDIX F4

RESULTS OF FUNCTIONAL PERFORMANCE MONITORING - KLEINKOPJE COLLIERY

F4-2

Contents

FUNCTIONAL PERFORMANCE ASSESSMENT
KLEINKOPJE COLLIERY
Summary of maintenance, defect score and repetitions

Site 1

Month (1994-1994)	Days since last maintenance	Defect (degree x extent)	Repetitions/day
September	1	70	43
January	2	49	53
November	2	60	44
July	3	72	59
April	3	88	89
March	4	77	79
February	5	60	23
August	6	86	69
October	8	75	74
June	8	76	11
May	9	78	24
December	11	79	143

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FUNCTIONAL PERFORMANCE ASSESSMENT
KLEINKOPJE COLLIERY
Summary of maintenance, defect score and repetitions

Site 2

Month (1994-1995)	Days since last maintenace	Defect (Degree x extent)	Repetitions/day
April	1	76	62
July	2	63	3
November	2	70	42
January	2	71	87
June	3	79	13
October	3	82	68
September	4	79	43
December	5	75	8
May	5	90	23
February	6	75	54
August	6	88	12
March	9	88	73

FUNCTIONAL PERFORMANCE ASSESSMENT
KLEINKOPJE COLLIERY
Summary of defect (degree x extent) score

Site 1 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matrl.	Dust	Stones fixed	Stones loose	Cracks longtd	Cracks slip	Cracks croc	TOTAL DEFECT
May	1	4	6	12	25	12	9	4	1	4	78
June	2	4	6	9	25	12	9	4	1	4	76
July	4	6	9	12	12	12	9	1	1	6	72
August	4	6	6	20	20	12	12	1	1	4	86
September	6	9	6	8	16	12	9	1	1	2	70
October	8	9	6	12	16	12	9	1	1	1	75
November	4	4	6	9	16	12	6	1	1	1	60
December	6	6	12	9	20	12	6	1	1	6	79
January	2	4	6	6	9	12	4	1	1	4	49
February	4	4	12	12	12	3	6	2	1	4	60
March	2	4	4	12	25	12	9	4	1	4	77
April	4	4	9	20	20	12	12	2	1	4	88
Average dry season (May-Aug)	2.75	5.00	6.75	13.25	20.50	12.00	9.75	2.50	1.00	4.50	
Average wet season (Sept-Apr)	4.50	5.50	7.63	11.00	16.75	10.88	7.63	1.63	1.00	3.25	
Annual average	3.92	5.33	7.33	11.75	18.00	11.25	8.33	1.92	1.00	3.67	

FUNCTIONAL PERFORMANCE ASSESSMENT
KLEINKOPJE COLLIERY
Summary of defect (degree x extent) score

Site 2 Month (1994-1995)	Pothole	Corrug.	Rutting	Loose matrl.	Dust	Stones fixed	Stones loose	Cracks longtd	Cracks slip	Cracks croc	TOTAL DEFECT
May	6	6	9	12	25	6	12	1	1	12	90
June	6	6	12	12	12	8	12	1	1	9	79
July	4	4	4	12	16	6	9	1	1	6	63
August	5	9	6	10	25	8	16	1	1	6	87
September	4	6	6	10	25	8	12	1	1	6	79
October	6	4	9	12	16	12	12	1	1	9	82
November	4	4	9	12	12	6	12	1	1	9	70
December	4	6	12	12	12	6	12	1	1	9	75
January	4	4	4	12	0	12	9	1	1	4	51
February	4	6	12	12	12	6	12	1	1	9	75
March	4	9	9	15	25	6	12	1	1	6	88
April	4	4	1	20	25	6	12	1	1	2	76
Average dry season (May-Aug)	5.25	6.25	7.75	11.50	19.50	7.00	12.25	1.00	1.00	8.25	
Average wet season (Sept-Apr)	4.25	5.38	7.75	13.13	15.88	7.75	11.63	1.00	1.00	6.75	
Annual average	4.58	5.67	7.75	12.58	17.08	7.50	11.83	1.00	1.00	7.25	

Kleinkopje Mine	**Site 1**	
Date of assessment	May 94	
Days since last maintenance	9	
Maintenance frequency/7 days	2	
Traffic (t/day)	2707	
Truck type(s)	CH120/130	
Truck factor (t)	115	
Truck repetitions per day	24	
Truck speed (km/h)	30	
Moisture conditions	Dry	
Rainfall for month (mm)	0	
COMMENTS Unloaded less cracks degree and rutting degree - local blading as reqd.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	1
Corrugations	3	3
Rutting	3	4
Loose material	3	4
Dustiness	5	5
Stoniness - fixed	3	4
Stoniness - loose	3	3
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	3	3
Sum Degree x extent		**94**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

Kleinkopje Mine	**Site 1**	
Date of assessment	Jun 94	
Days since last maintenance	8	
Maintenance frequency/7 days	1	
Traffic (t/day)	1265	
Truck type(s)	CH120/130	
Truck factor (t)	115	
Truck repetitions per day	11	
Truck speed (km/h)	30	
Moisture conditions	Moist	
Rainfall for month (mm)	0	
COMMENTS Dust and loose material, less on unload (faster) side.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	1
Corrugations	3	3
Rutting	3	4
Loose material	3	5
Dustiness	5	5
Stoniness - fixed	3	4
Stoniness - loose	3	3
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	3	2
Sum Degree x extent		**95**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

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Kleinkopje Mine	**Site 1**	
Date of assessment	Jul 94	
Days since last maintenance	3	
Maintenance frequency/7 days	1	
Traffic (t/day)	6752	
Truck type(s)	Ch120/130	
Truck factor (t)	115	
Truck repetitions per day	59	
Truck speed (km/h)	30	
Moisture conditions	Dry	
Rainfall for month (mm)	0	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	3	3
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	3	4
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**72**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	1	

Kleinkopje Mine	**Site 1**	
Date of assessment	Aug 94	
Days since last maintenance	6	
Maintenance frequency/7 days	1	
Traffic (t/day)	7946	
Truck type(s)	Ch120/130	
Truck factor (t)	115	
Truck repetitions per day	69	
Truck speed (km/h)	30	
Moisture conditions	dry	
Rainfall for month (mm)	0	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	2	3
Loose material	4	5
Dustiness	4	5
Stoniness - fixed	3	4
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**86**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

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Kleinkopje Mine	**Site 1**	
Date of assessment	Sept 94	
Days since last maintenance	1	
Maintenance frequency/7 days	2	
Traffic (t/day)	4996	
Truck type(s)	Ch120/130	
Truck factor (t)	115	
Truck repetitions per day	43	
Truck speed (km/h)	30	
Moisture conditions	dry	
Rainfall for month (mm)	24	
COMMENTS Minor croc cracks loaded side only.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	3	3
Rutting	2	3
Loose material	2	4
Dustiness	4	4
Stoniness - fixed	3	4
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	2
Sum Degree x extent		**70**
Skid resistance - wet	2	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

Kleinkopje Mine	**Site 1**	
Date of assessment	Oct 94	
Days since last maintenance	8	
Maintenance frequency/7 days	2	
Traffic (t/day)	8558	
Truck type(s)	Ch120/130	
Truck factor (t)	115	
Truck repetitions per day	74	
Truck speed (km/h)	30	
Moisture conditions	Moist	
Rainfall for month (mm)	64	
COMMENTS More stones visible - erosion of fines to road side unloaded. Not on loadside.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	4
Corrugations	3	3
Rutting	2	3
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	3	4
Stoniness - loose	3	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		**75**
Skid resistance - wet	2	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

Kleinkopje Mine	**Site 1**	
Date of assessment	Nov 94	
Days since last maintenance	2	
Maintenance frequency/7 days	2	
Traffic (t/day)	5043	
Truck type(s)	Ch120/130	
Truck factor (t)	115	
Truck repetitions per day	44	
Truck speed (km/h)	30	
Moisture conditions	Dry	
Rainfall for month (mm)	54.5	
COMMENTS Dust on slower load side maybe spillage, sl less unloaded but faster.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose material	3	3
Dustiness	4	4
Stoniness - fixed	3	4
Stoniness - loose	2	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	1
Sum Degree x extent		**60**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

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Kleinkopje Mine	**Site 1**	
Date of assessment	Dec 94	
Days since last maintenance	11	
Maintenance frequency/7 days	2	
Traffic (t/day)	16434	
Truck type(s)	Ch120/130	
Truck factor (t)	115	
Truck repetitions per day	143	
Truck speed (km/h)	30	
Moisture conditions	dry	
Rainfall for month (mm)	93	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	2	3
Rutting	3	4
Loose material	3	3
Dustiness	4	5
Stoniness - fixed	3	4
Stoniness - loose	2	3
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**79**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

Kleinkopje Mine	**Site 1**	
Date of assessment	Jan 95	
Days since last maintenance	2	
Maintenance frequency/7 days	1	
Traffic (t/day)	6082	
Truck type(s)	CH120/130	
Truck factor (t)	115	
Truck repetitions per day	53	
Truck speed (km/h)	30	
Moisture conditions	Moist	
Rainfall for month (mm)	84.6	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	1
Corrugations	2	2
Rutting	2	3
Loose material	2	3
Dustiness	3	3
Stoniness - fixed	3	4
Stoniness - loose	2	2
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**49**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

Kleinkopje Mine	**Site 1**	
Date of assessment	Feb 95	
Days since last maintenance	5	
Maintenance frequency/7 days	1	
Traffic (t/day)	2691	
Truck type(s)	Ch120/130	
Truck factor (t)	115	
Truck repetitions per day	23	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	64	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	4
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	1	3
Stoniness - loose	2	3
Cracks - longitudinal	1	2
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**60**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

Kleinkopje Mine	**Site 1**	
Date of assessment	Mar 95	
Days since last maintenance	4	
Maintenance frequency/7 days	2	
Traffic (t/day)	9091.39	
Truck type(s)	Ch120/130	
Truck factor	115	
Truck repetitions per day	79	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	108	
COMMENTS Varaible tonnage effects noticeable, slight potholing more unloaded side.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	1	2
Corrugations	2	2
Rutting	2	2
Loose material	3	4
Dustiness	5	5
Stoniness - fixed	3	4
Stoniness - loose	3	3
Cracks - longitudinal	2	2
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**77**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

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Kleinkopje Mine	**Site 1**	
Date of assessment	Apr 95	
Days since last maintenance	3	
Maintenance frequency/7 days	2	
Traffic (t/day)	10257.52	
Truck type(s)	Ch120/130	
Truck factor	115	
Truck repetitions per day	89	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	112	
COMMENTS Recent on sight blading done, some potholes due to stoniness, obv unloaded		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose material	4	5
Dustiness	4	5
Stoniness - fixed	3	4
Stoniness - loose	3	4
Cracks - longitudinal	1	2
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**88**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	2	
Erosion - cross	2	
Drainage - on road	1	
Drainage - side of road	1	

Kleinkopje Mine	**Site 2**	
Date of assessment	May 94	
Days since last maintenance	5	
Maintenance frequency/7 days	1	
Traffic (t/day)	2791	
Truck type(s)	Ch120/130, 630E	
Truck factor (t)	122	
Truck repetitions per day	23	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	0	
COMMENTS Cracks form mud bounded blocks which tend to lift on load side		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	2	3
Rutting	3	3
Loose material	3	4
Dustiness	5	5
Stoniness - fixed	2	3
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	3	4
Sum Degree x extent		**90**
Skid resistance - wet	4	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	3	

Kleinkopje Mine	**Site 2**	
Date of assessment	Jun 94	
Days since last maintenance	3	
Maintenance frequency/7 days	1	
Traffic (t/day)	1573	
Truck type(s)	Ch120/130, 630E	
Truck factor (t)	122	
Truck repetitions per day	13	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	0	
COMMENTS Ruts more pronounced load side, unload side less loose on road.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	3	3
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	3	4
Stoniness - loose	3	4
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	3	3
Sum Degree x extent		**82**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	2	
Erosion - cross	2	
Drainage - on road	3	
Drainage - side of road	3	

Kleinkopje Mine	**Site 2**	
Date of assessment	Jul 94	
Days since last maintenance	2	
Maintenance frequency/7 days	1	
Traffic (t/day)	320	
Truck type(s)	Ch120/130, 630E	
Truck factor (t)	122	
Truck repetitions per day	3	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	0	
COMMENTS Recent on sight blading, v dusty and problem with skid resistance.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose material	4	3
Dustiness	4	5
Stoniness - fixed	3	4
Stoniness - loose	3	3
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	2	2
Sum Degree x extent		**71**
Skid resistance - wet	3	
Skid resistance - dry	5	
Erosion - longitudional	1	
Erosion - cross	1	
Drainage - on road	2	
Drainage - side of road	2	

Kleinkopje Mine	**Site 2**	
Date of assessment	Aug 94	
Days since last maintenance	6	
Maintenance frequency/7 days	1	
Traffic (t/day)	1481	
Truck type(s)	Ch120/130, 630E	
Truck factor (t)	122	
Truck repetitions per day	12	
Truck speed (km/h)	40	
Moisture conditions	dry	
Rainfall for month (mm)	0	
COMMENTS Loose material at centre and edge of road, unload less fine loose (faster)		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	3	2
Corrugations	3	3
Rutting	3	2
Loose material	2	5
Dustiness	5	5
Stoniness - fixed	2	4
Stoniness - loose	4	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	3	2
Sum Degree x extent		**88**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

Kleinkopje Mine	**Site 2**	
Date of assessment	Sep 94	
Days since last maintenance	4	
Maintenance frequency/7 days	1	
Traffic (t/day)	5185	
Truck type(s)	Ch120/130, 630E	
Truck factor (t)	122	
Truck repetitions per day	43	
Truck speed (km/h)	40	
Moisture conditions	Dry	
Rainfall for month (mm)	24	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	3	2
Loose material	2	5
Dustiness	5	5
Stoniness - fixed	2	4
Stoniness - loose	3	4
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	3	2
Sum Degree x extent		**79**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	3	

Kleinkopje Mine	**Site 2**	
Date of assessment	Oct 94	
Days since last maintenance	3	
Maintenance frequency/7 days	1	
Traffic (t/day)	8327	
Truck type(s)	Ch120/130, 630E	
Truck factor (t)	122	
Truck repetitions per day	68	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	64	
COMMENTS Loose at road edge.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	3
Corrugations	2	3
Rutting	3	4
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	2	4
Stoniness - loose	3	4
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	3	3
Sum Degree x extent		**79**
Skid resistance - wet	4	
Skid resistance - dry	4	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	3	

F4-25

Kleinkopje Mine	**Site 2**	
Date of assessment	Nov 94	
Days since last maintenance	2	
Maintenance frequency/7 days	1	
Traffic (t/day)	5086	
Truck type(s)	Ch120/130, 630E	
Truck factor (t)	122	
Truck repetitions per day	42	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	54.5	
COMMENTS Side of road bladed material onto road. Still dusty, poor skid resistance.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	2	3
Stoniness - loose	3	4
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	3	3
Sum Degree x extent		**70**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	3	

Kleinkopje Mine	**Site 2**	
Date of assessment	Dec 94	
Days since last maintenance	5	
Maintenance frequency/7 days	1	
Traffic (t/day)	947	
Truck type(s)	Ch120/130, 630E	
Truck factor (t)	122	
Truck repetitions per day	8	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	93	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	3	4
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	2	3
Stoniness - loose	3	4
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	3	3
Sum Degree x extent		**75**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	1	

Kleinkopje Mine	**Site 2**	
Date of assessment	Jan 95	
Days since last maintenance	2	
Maintenance frequency/7 days	1	
Traffic (t/day)	10660	
Truck type(s)	Ch120/130, 630E	
Truck factor (t)	122	
Truck repetitions per day	87	
Truck speed (km/h)	40	
Moisture conditions	Moist	
Rainfall for month (mm)	84.6	
COMMENTS Recent rain 36hrs. Road slightly cut up on bends. Dusty despite rain.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose material	3	4
Dustiness	4	4
Stoniness - fixed	2	3
Stoniness - loose	3	3
Cracks - longitudional	1	1
Cracks - slip	1	1
Cracks - crocodile	2	3
Sum Degree x extent		**63**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudional	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	3	

Kleinkopje Mine **Site 2**

Date of assessment	Feb 95
Days since last maintenance	6
Maintenance frequency/7 days	1
Traffic (t/day)	6591
Truck type(s)	Ch120/130, 630E
Truck factor (t)	122
Truck repetitions per day	54
Truck speed (km/h)	40
Moisture conditions	Dry
Rainfall for month (mm)	64

WEARING COURSE SURFACE

	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	3	4
Loose material	3	4
Dustiness	3	4
Stoniness - fixed	2	3
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	3	3
Sum Degree x extent		**75**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	3	
Drainage - side of road	2	

Kleinkopje Mine	**Site 2**	
Date of assessment	Mar 95	
Days since last maintenance	9	
Maintenance frequency/7 days	1	
Traffic (t/day)	8845.74	
Truck type(s)	Ch120/130, 630E	
Truck factor	122	
Truck repetitions per day	73	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	108	
COMMENTS		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	3	3
Rutting	3	3
Loose material	3	5
Dustiness	5	5
Stoniness - fixed	2	3
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	3	2
Sum Degree x extent		**88**
Skid resistance - wet	3	
Skid resistance - dry	3	
Erosion - longitudinal	1	
Erosion - cross	2	
Drainage - on road	2	
Drainage - side of road	4	

Kleinkopje Mine	**Site 2**	
Date of assessment	Apr 95	
Days since last maintenance	1	
Maintenance frequency/7 days	2	
Traffic (t/day)	7504.39	
Truck type(s)	Ch120/130, 630E	
Truck factor	122	
Truck repetitions per day	62	
Truck speed	40	
Moisture conditions	Dry	
Rainfall for month	112	
COMMENTS Smaller potholing evident unloaded side, rutting more loaded.		
WEARING COURSE SURFACE		
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	1	1
Loose material	4	5
Dustiness	5	5
Stoniness - fixed	2	3
Stoniness - loose	3	4
Cracks - longitudinal	1	1
Cracks - slip	1	1
Cracks - crocodile	1	2
Sum Degree x extent		**76**
Skid resistance - wet	3	
Skid resistance - dry	4	
Erosion - longitudinal	2	
Erosion - cross	3	
Drainage - on road	3	
Drainage - side of road	2	

APPENDIX G1

STATISTICAL DATA AND RESULTS OF ANALYSES

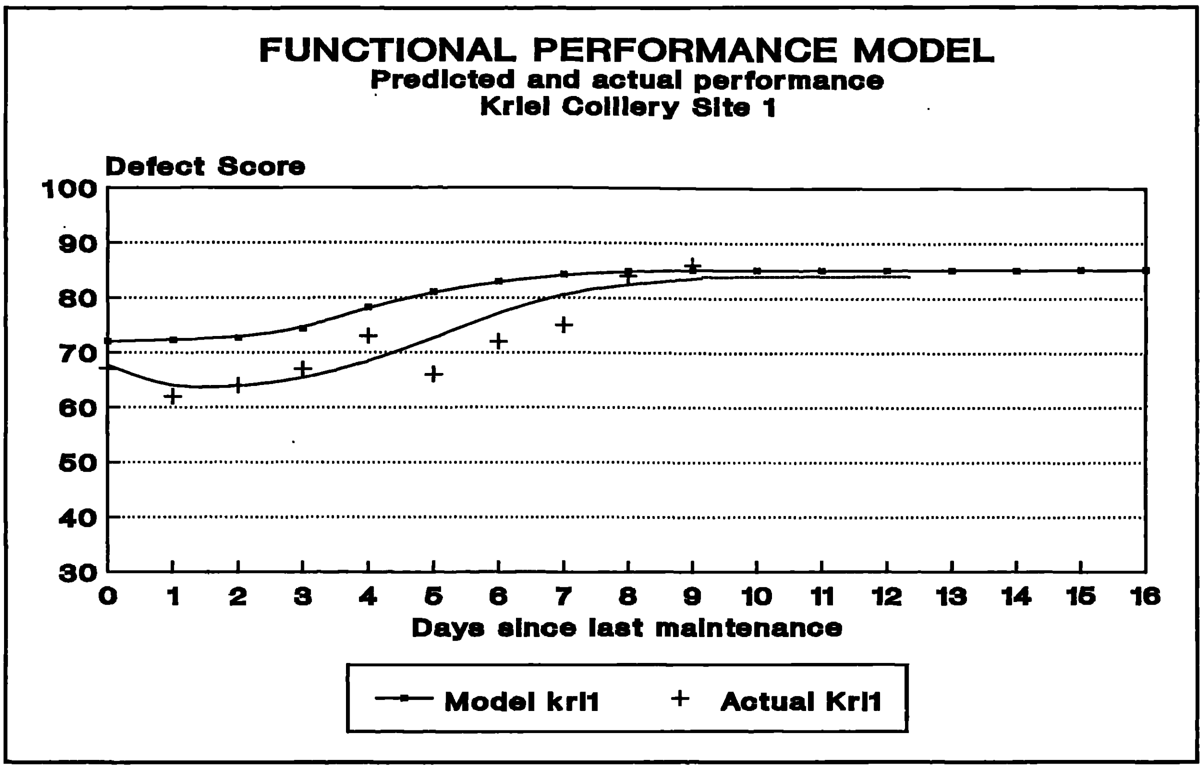
DEFECT PROGRESSION RATE MODEL

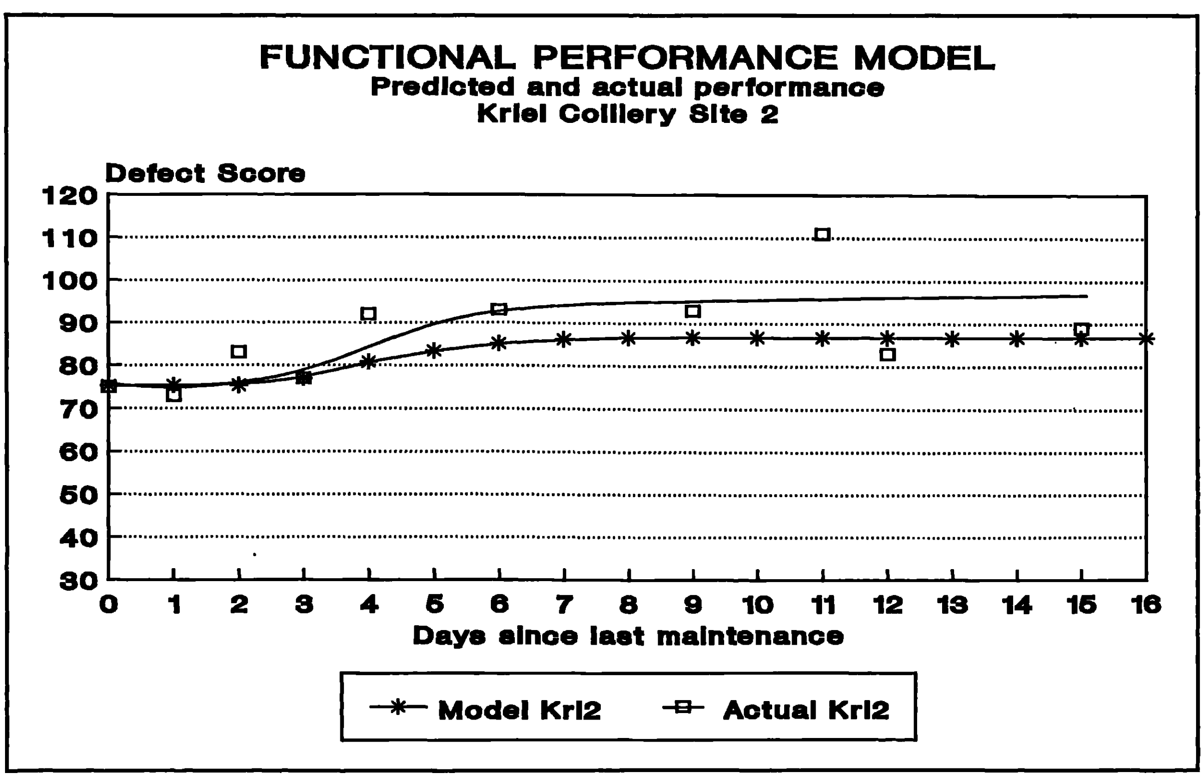
G1-2

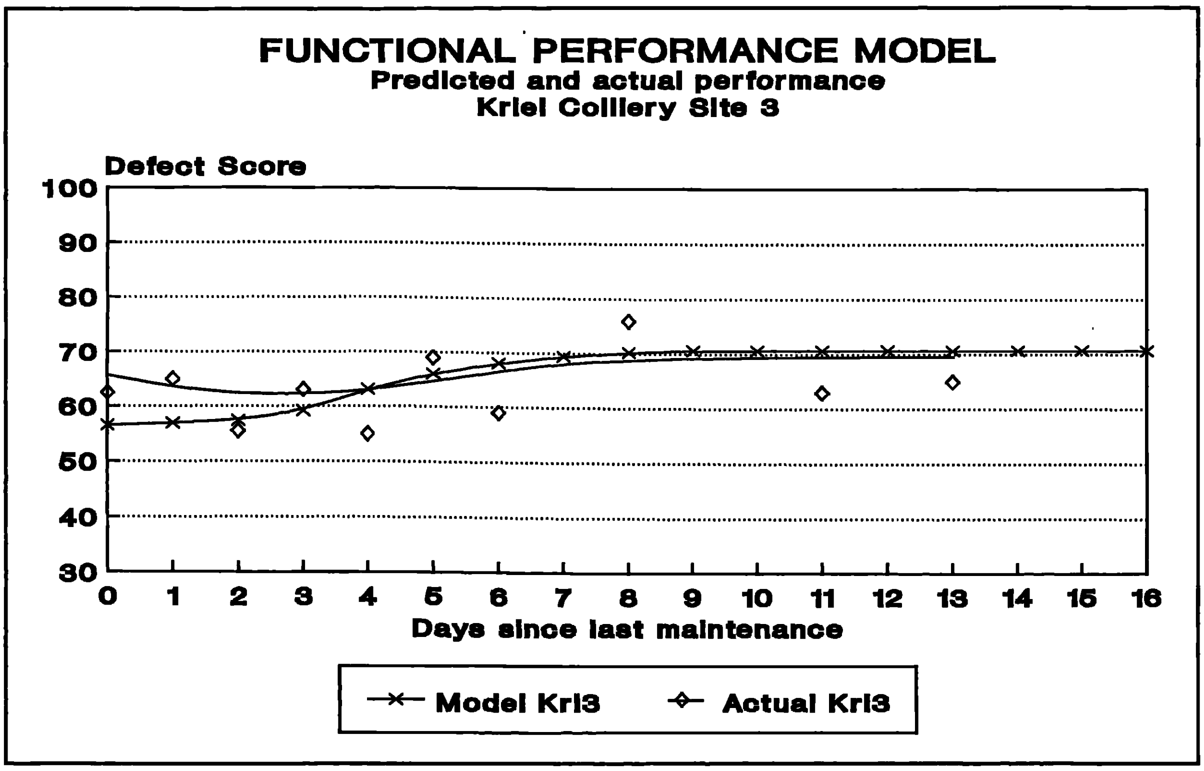
Contents

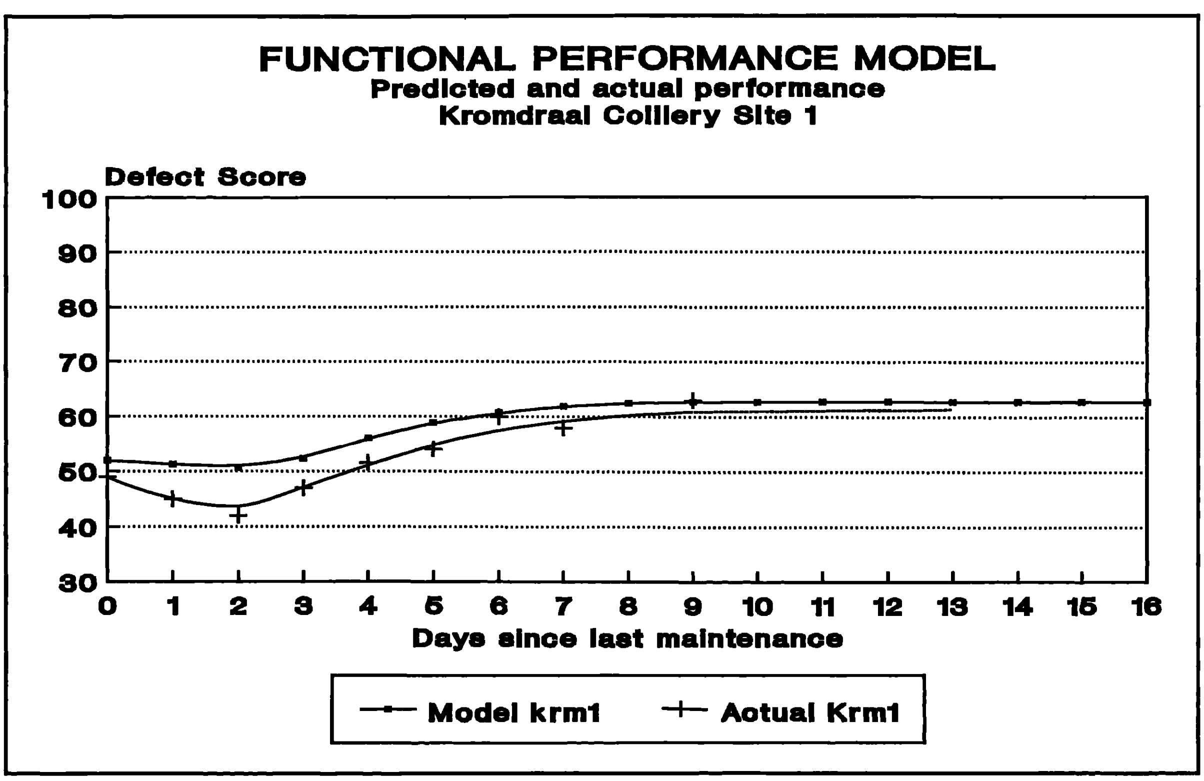
Comparison of actual against predicted defect score progression for each site.

G1-3

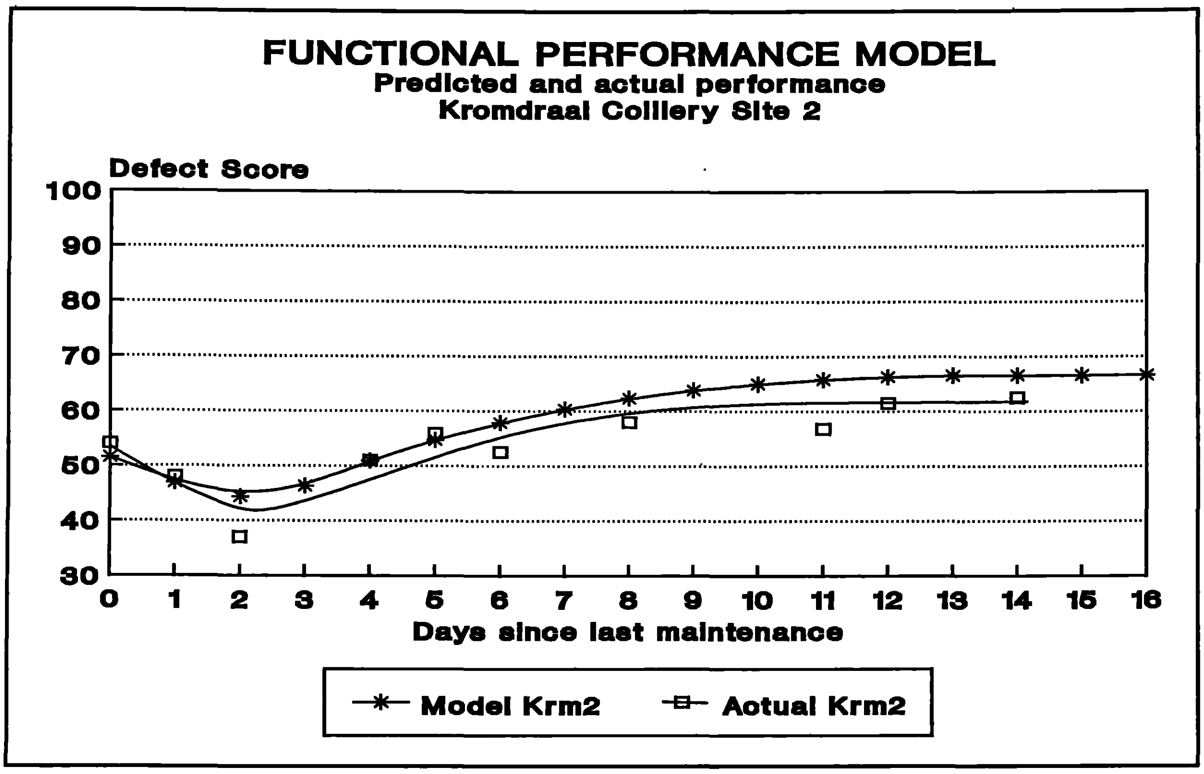

FUNCTIONAL PERFORMANCE MODEL
Predicted and actual performance
Kriel Colliery Site 1
Defect Score
100
90
80
70
60
50
40
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Days since last maintenance
Model kri1
Actual Kri1

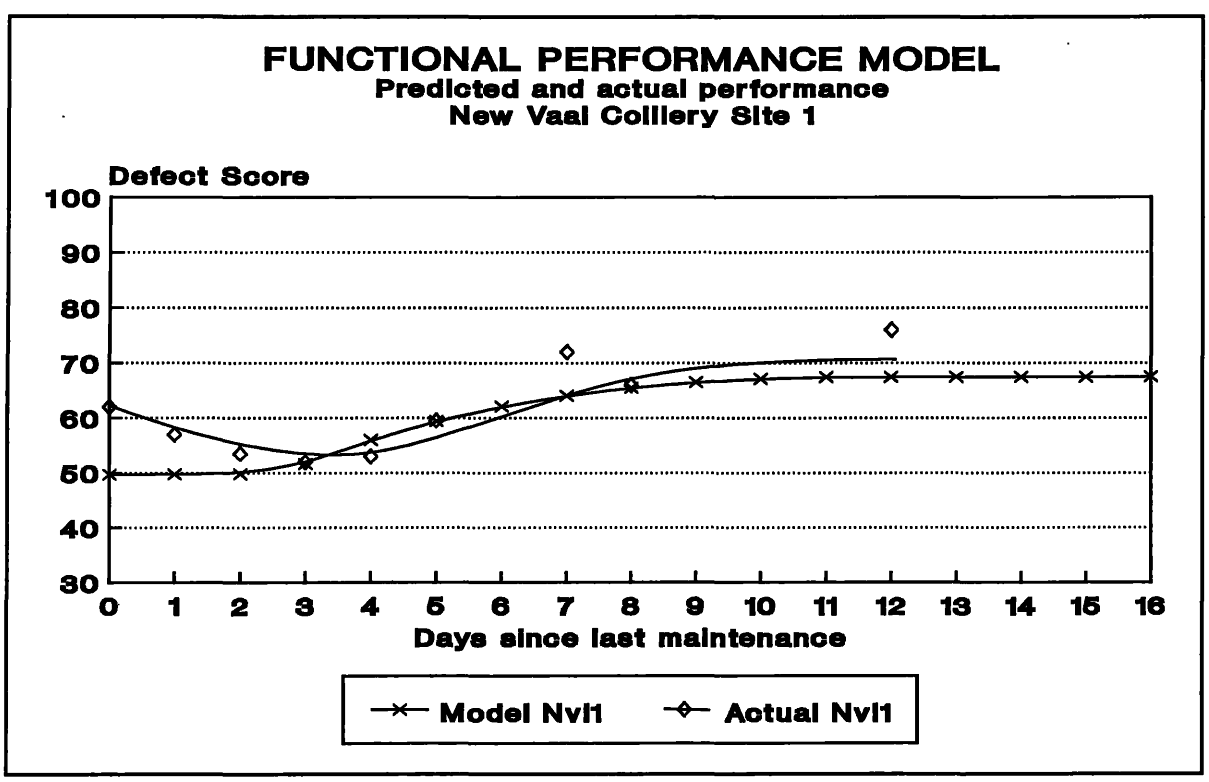

FUNCTIONAL PERFORMANCE MODEL
Predicted and actual performance
Kriel Colliery Site 2
Defect Score
120
110
100
90
80
70
60
50
40
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Days since last maintenance
Model Krl2
Actual Krl2

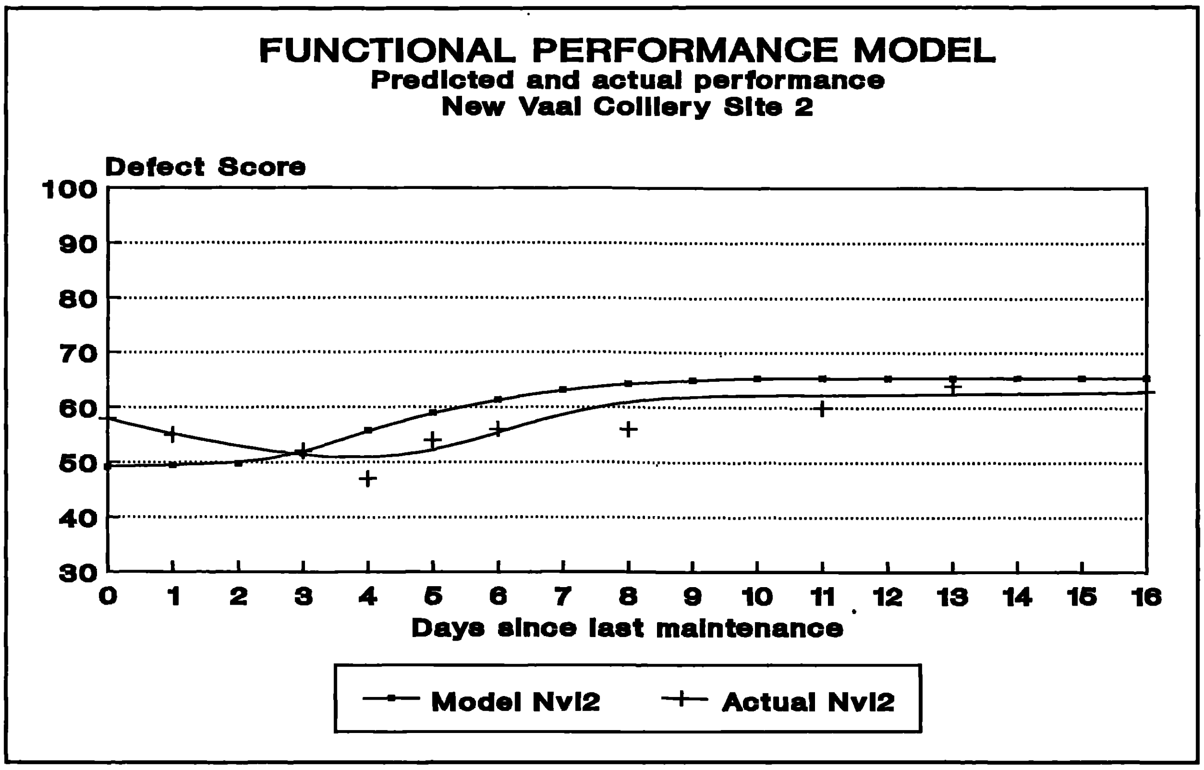

FUNCTIONAL PERFORMANCE MODEL
Predicted and actual performance
Kriel Colliery Site 3
Defect Score
100
90
80
70
60
50
40
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Days since last maintenance
Model Krl3
Actual Krl3

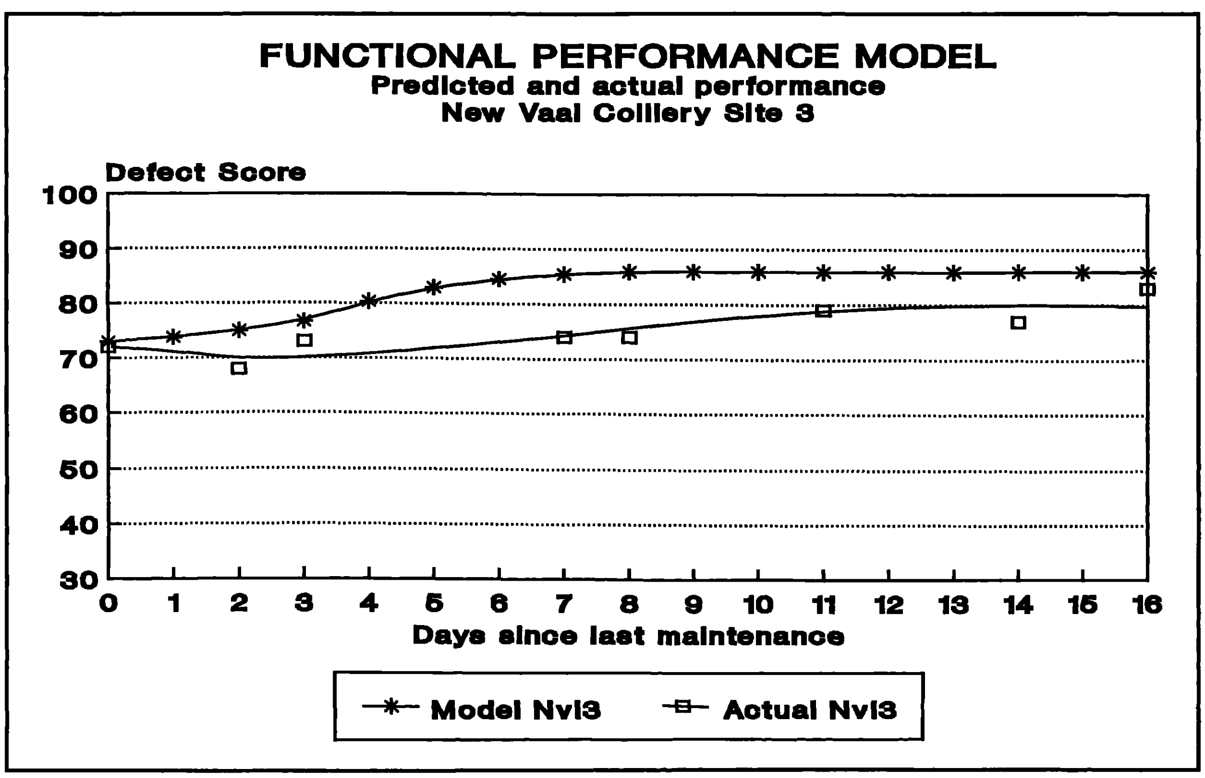

FUNCTIONAL PERFORMANCE MODEL
Predicted and actual performance
Kromdraal Colliery Site 1
Defect Score
100
90
80
70
60
50
40
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Days since last maintenance
Model krm1
Actual Krm1

G1-5


FUNCTIONAL PERFORMANCE MODEL
Predicted and actual performance
Kromdraal Colliery Site 2
Defect Score
100
90
80
70
60
50
40
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Days since last maintenance
Model Krm2
Actual Krm2


FUNCTIONAL PERFORMANCE MODEL
Predicted and actual performance
New Vaal Colliery Site 1
Defect Score
100
90
80
70
60
50
40
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Days since last maintenance
Model Nvl1
Actual Nvl1


FUNCTIONAL PERFORMANCE MODEL
Predicted and actual performance
New Vaal Colliery Site 2
Defect Score
100
90
80
70
60
50
40
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Days since last maintenance
Model Nvl2
Actual Nvl2


FUNCTIONAL PERFORMANCE MODEL
Predicted and actual performance
New Vaal Colliery Site 3
Defect Score
100
90
80
70
60
50
40
30
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Days since last maintenance
Model Nvl3
Actual Nvl3

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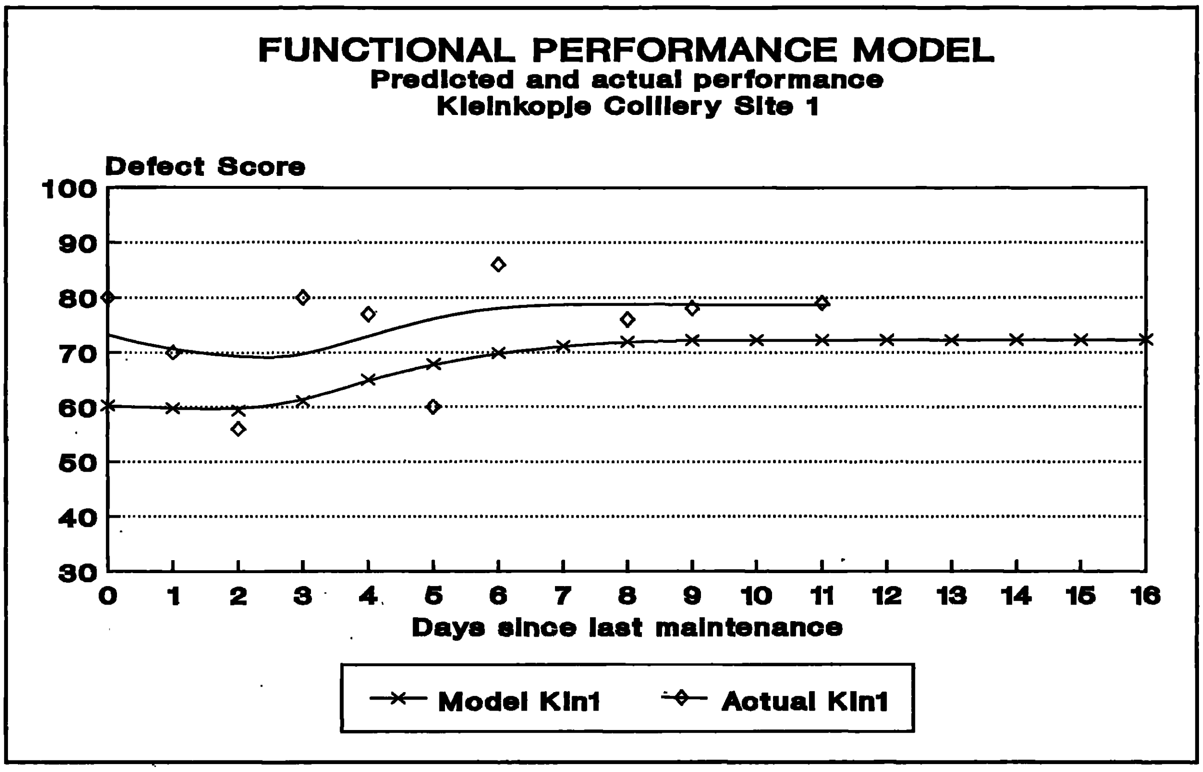

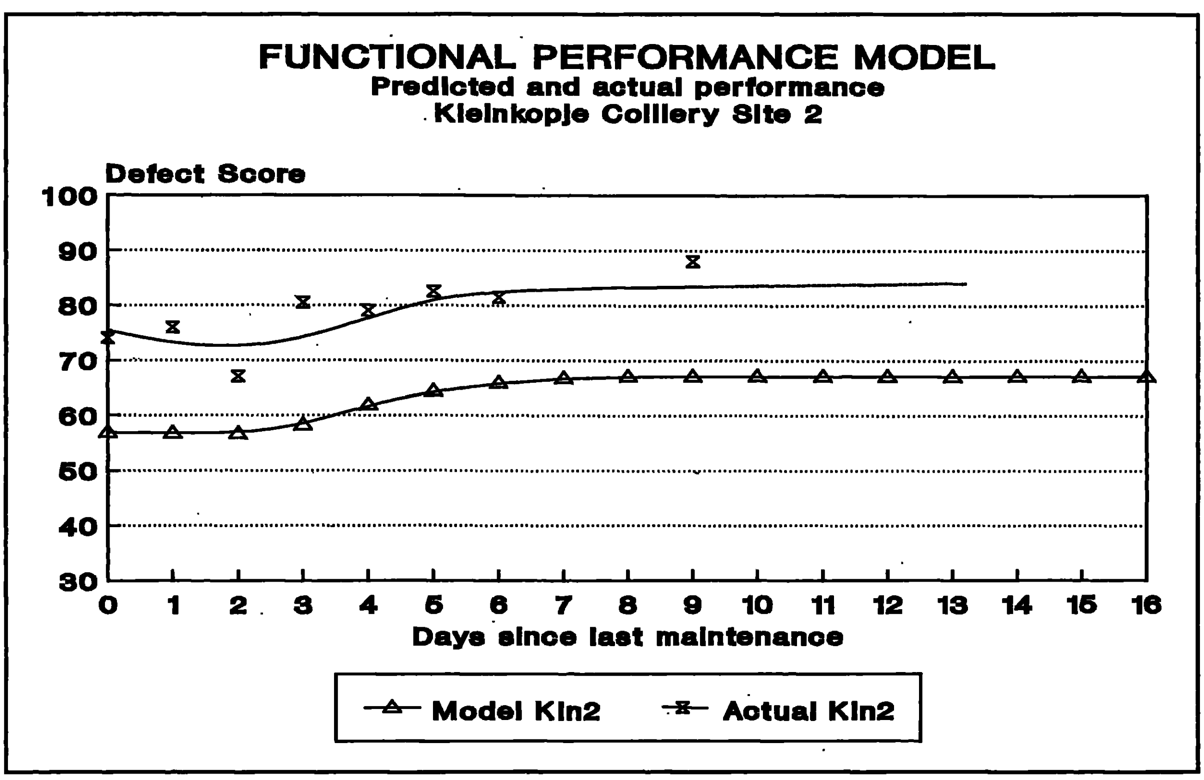

APPENDIX G2

STATISTICAL DATA AND RESULTS OF ANALYSES
MATERIAL PROPERTY MODELS

G2-2

Contents

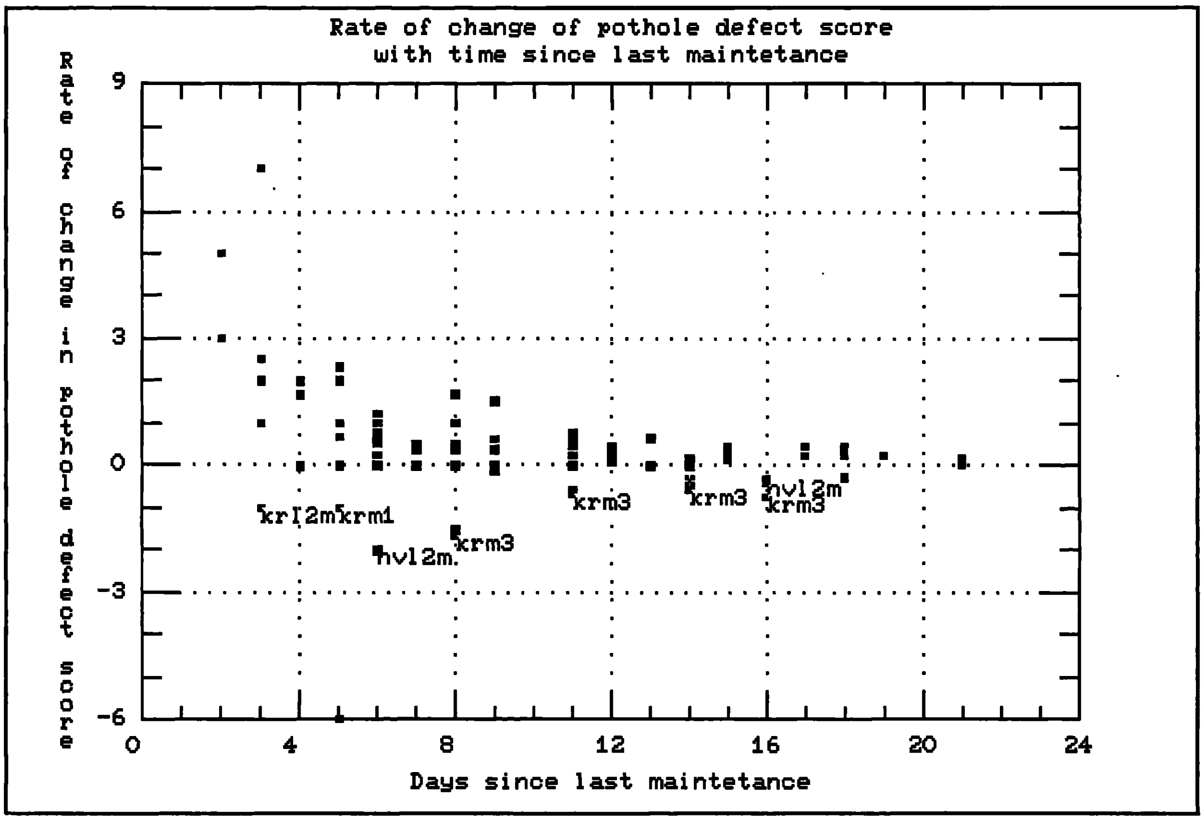

Figure 1 Rate of change of pothole defect score with days since last maintenance.

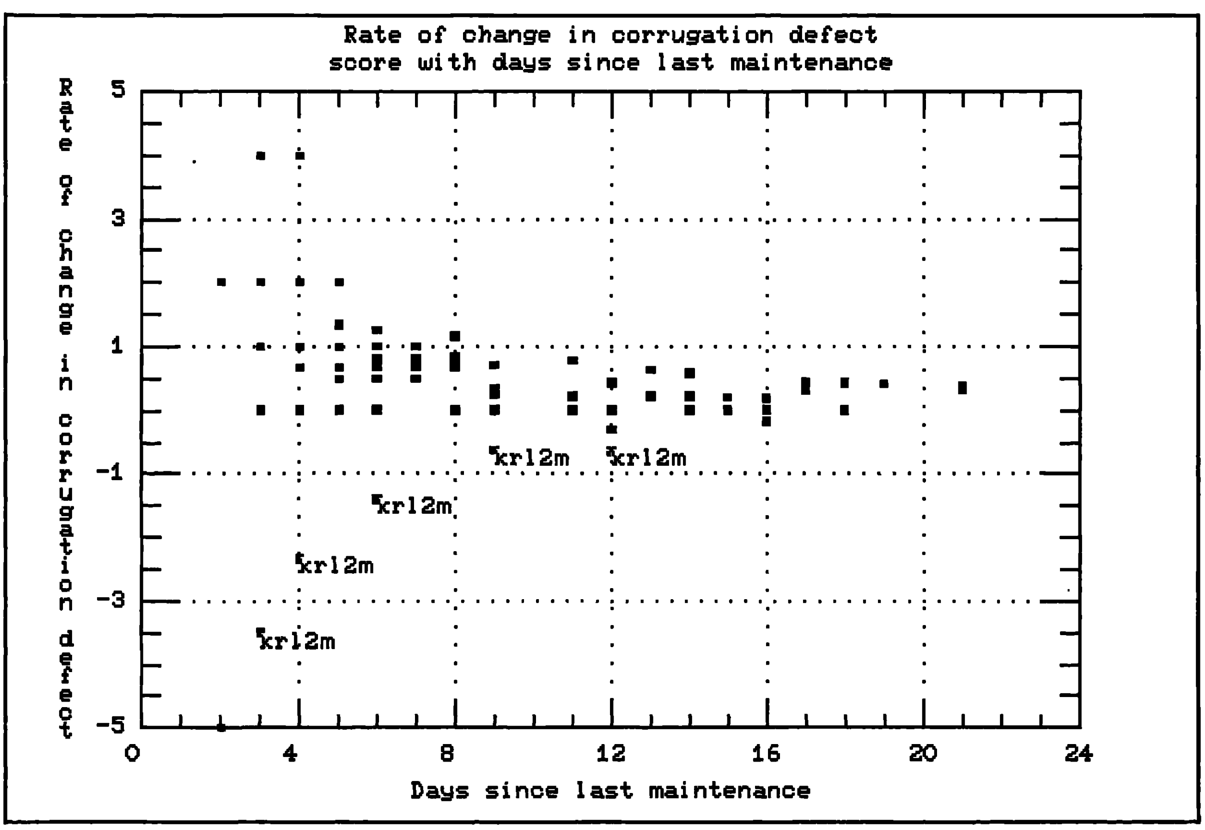

Figure 2 Rate of change of corrugation defect score with days since last maintenance.

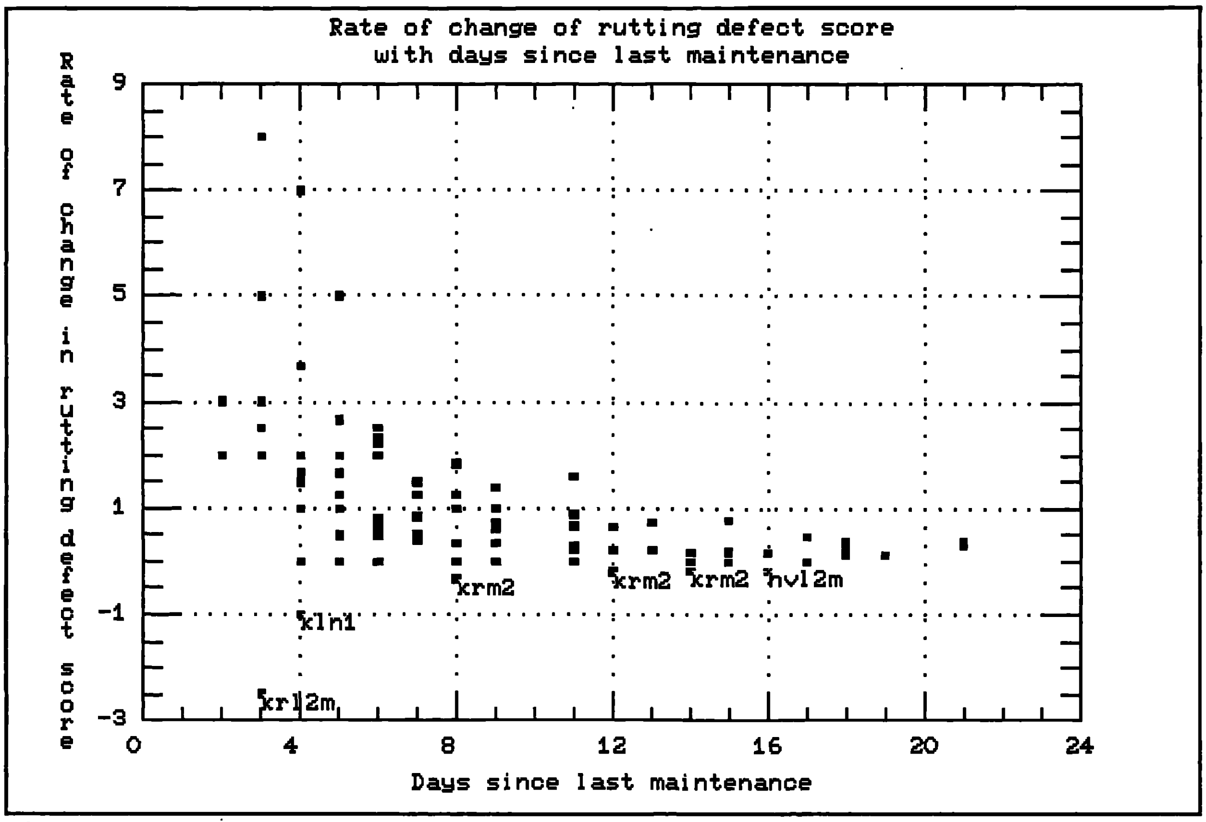

Figure 3 Rate of change of rutting defect score with days since last maintenance.

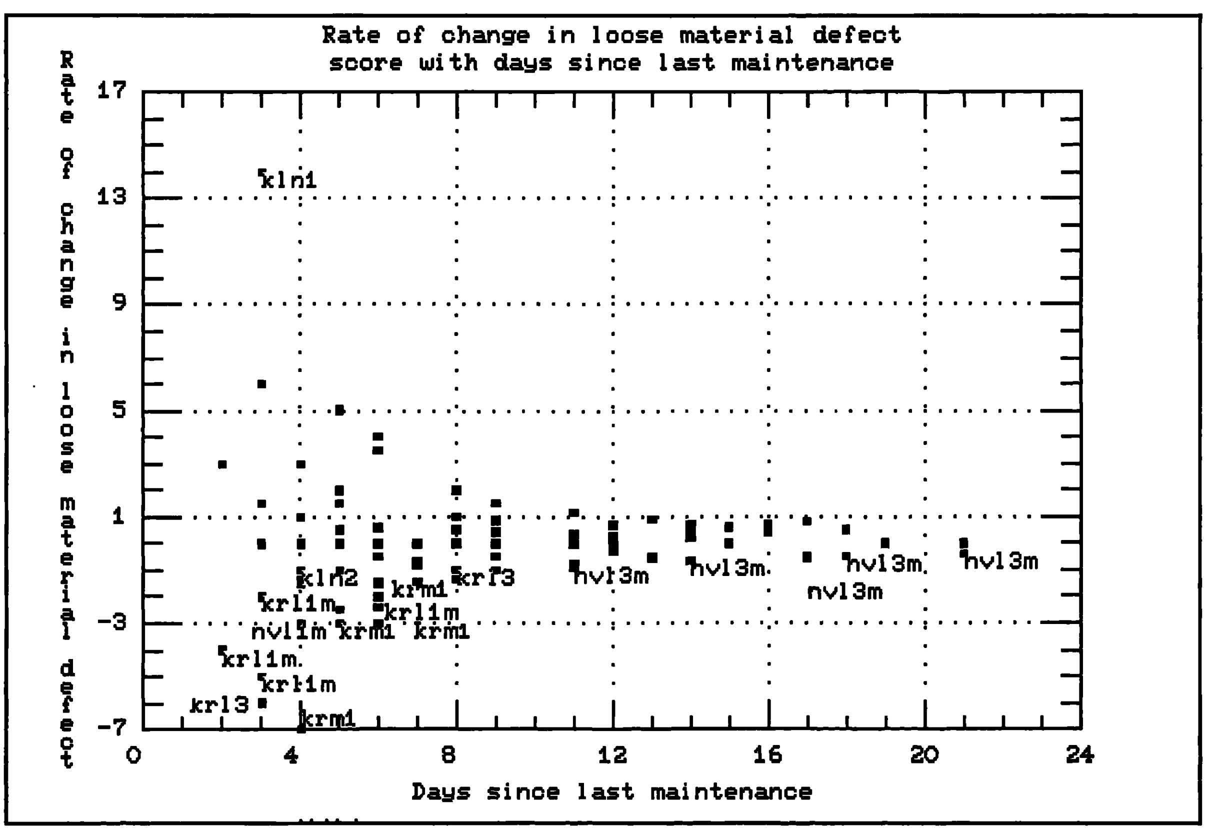

Figure 4 Rate of change of loose material defect score with days since last maintenance.

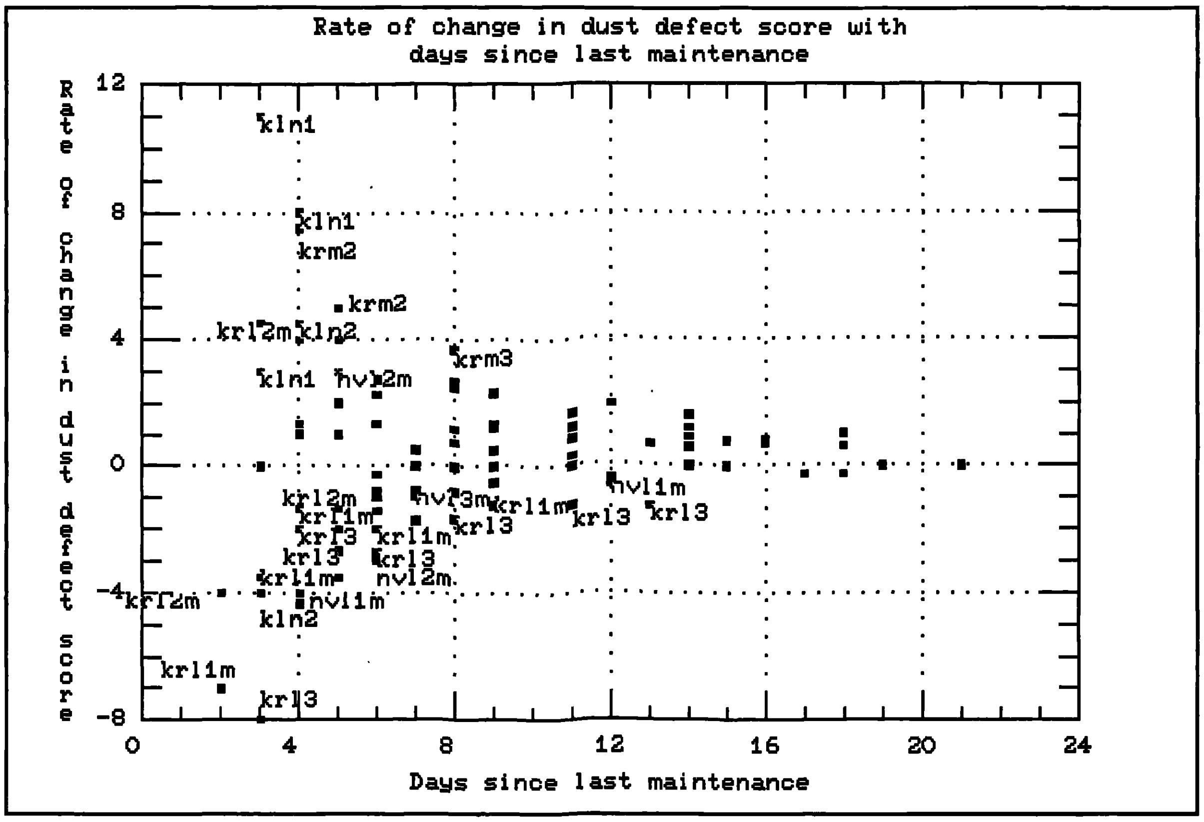

Figure 5 Rate of change of dustiness defect score with days since last maintenance.

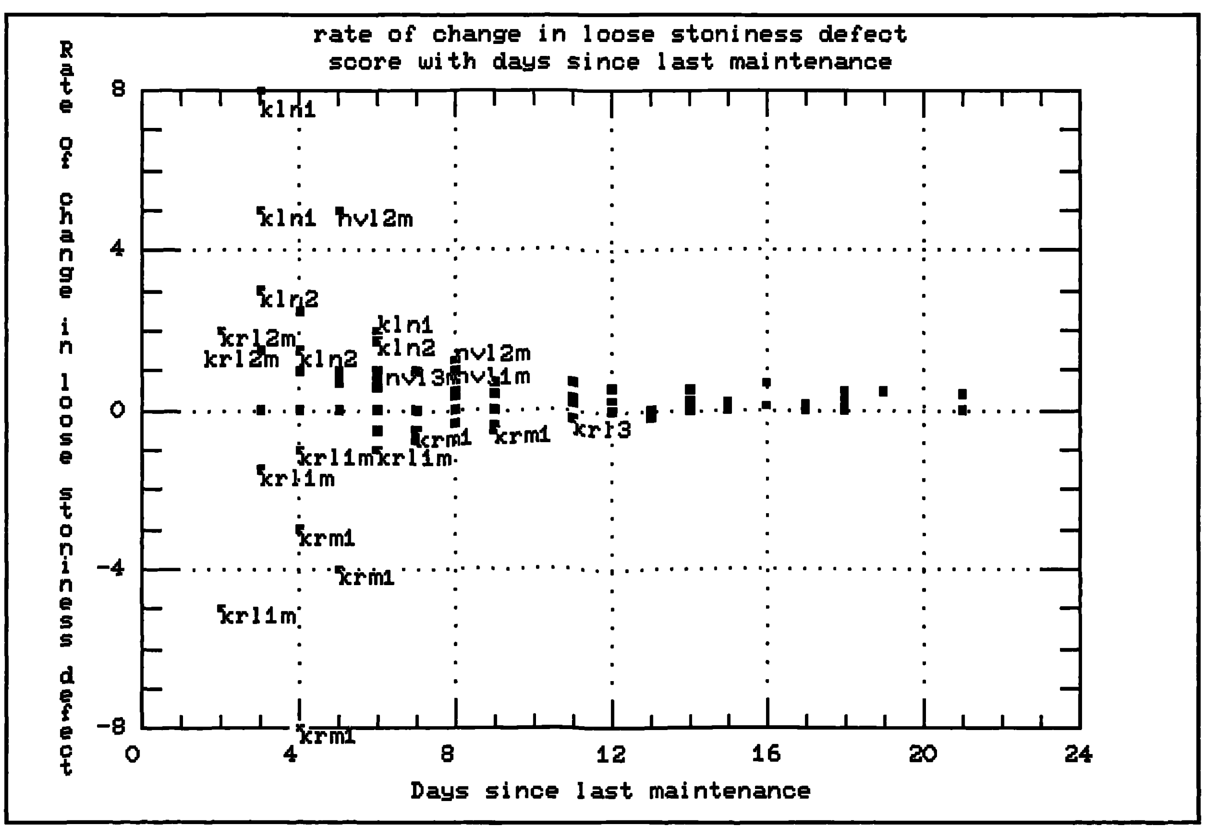

Figure 6 Rate of change of loose stoniness defect score with days since last maintenance.

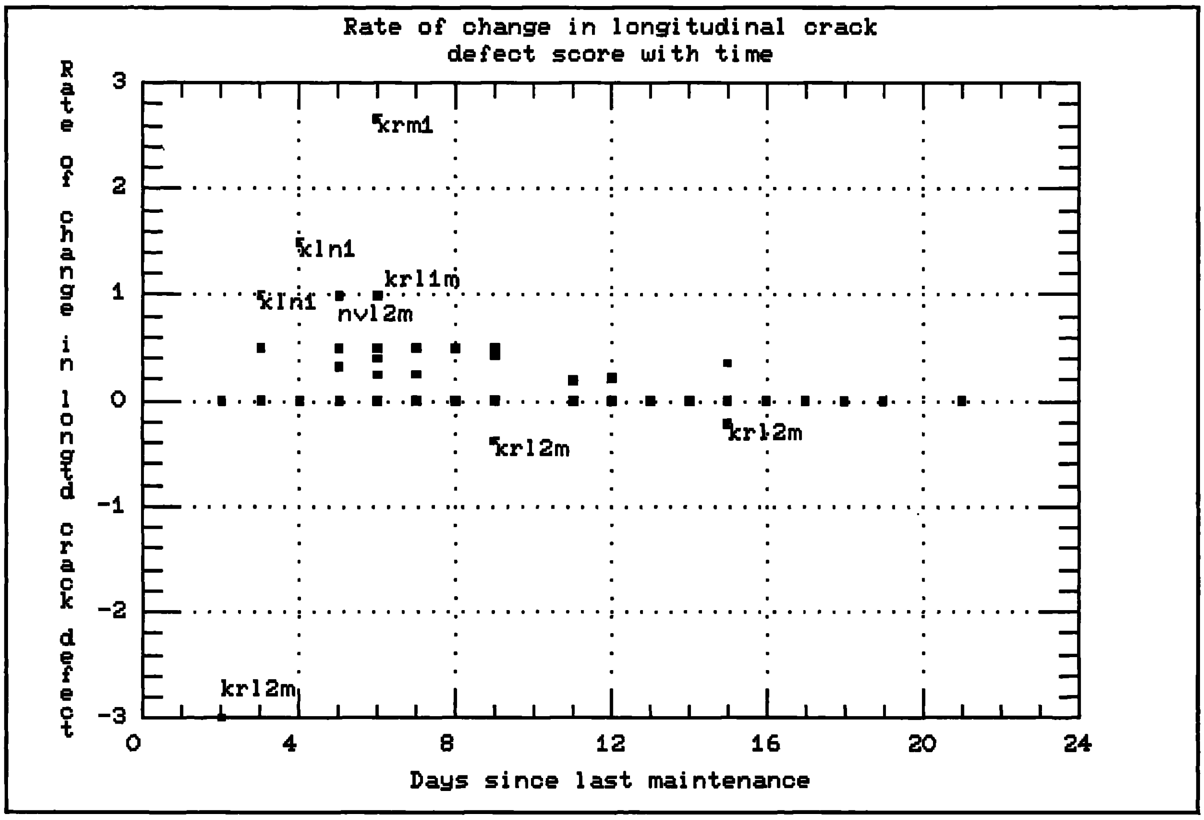

Figure 7 Rate of change of longitudinal crack defect score with days since last maintenance.

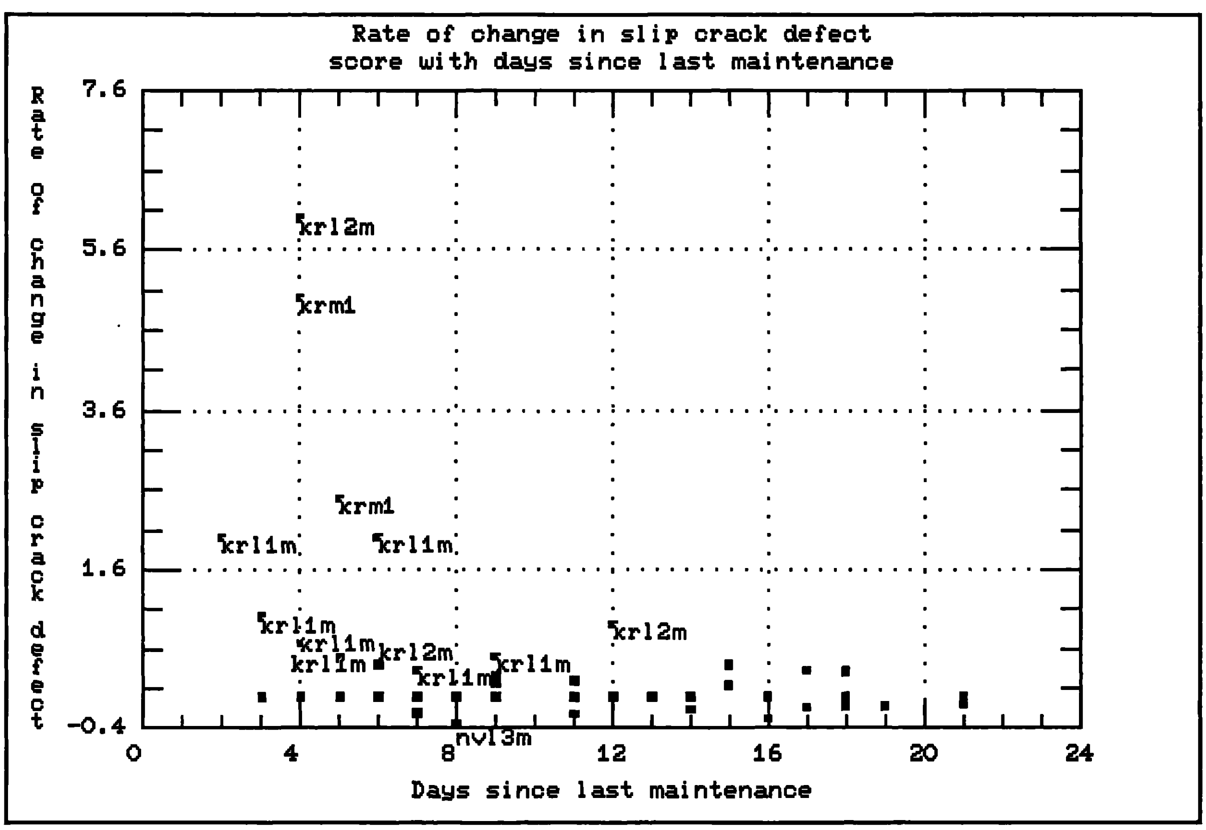

Figure 8 Rate of change of slip crack defect score with days since last maintenance.

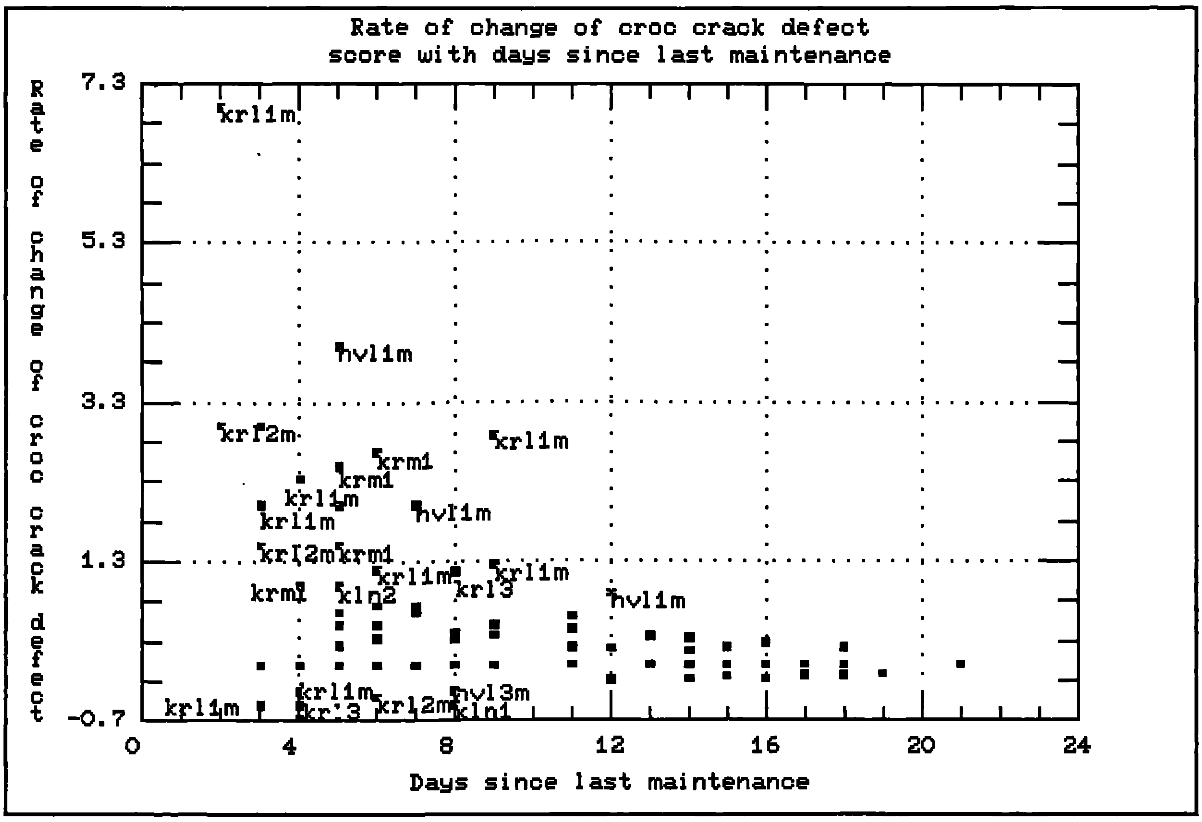

Figure 9 Rate of change of crocodile crack defect score with days since last maintenance.

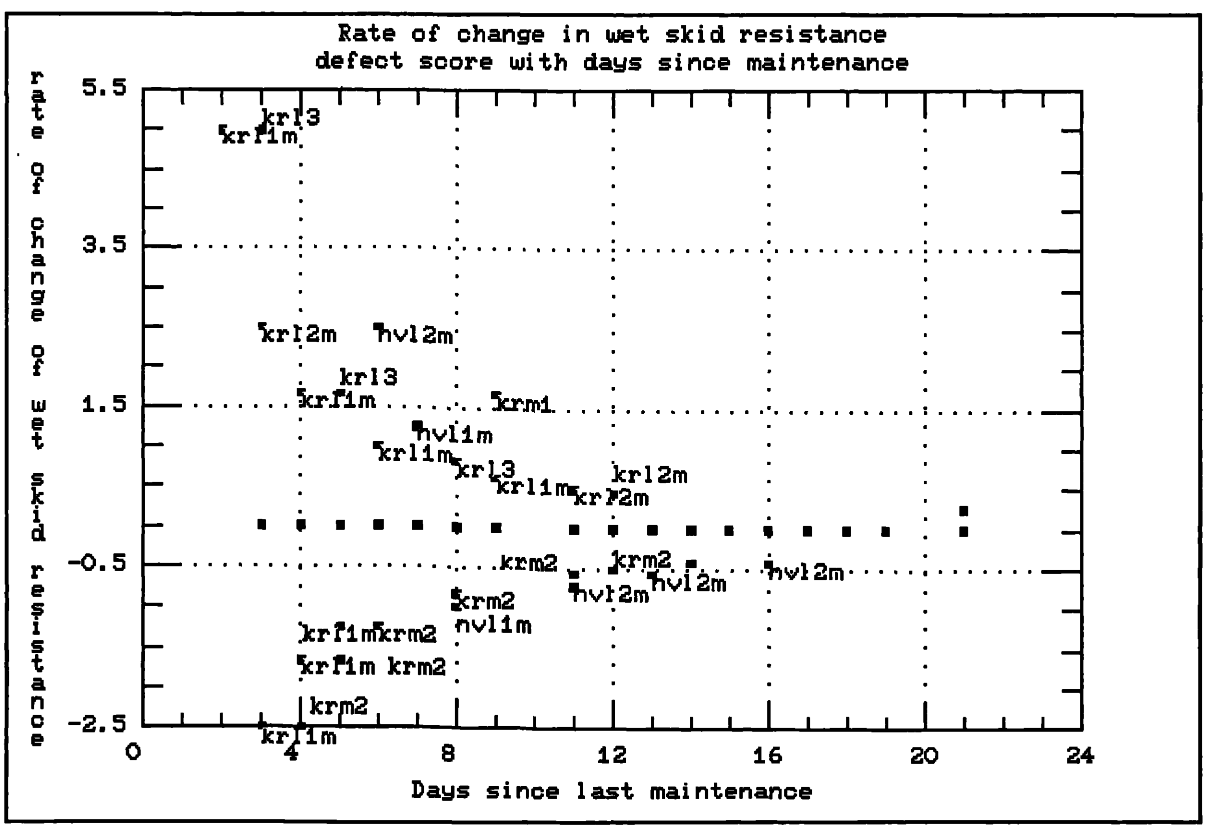

Figure 10 Rate of change of wet skid resistance defect score with days since last maintenance.

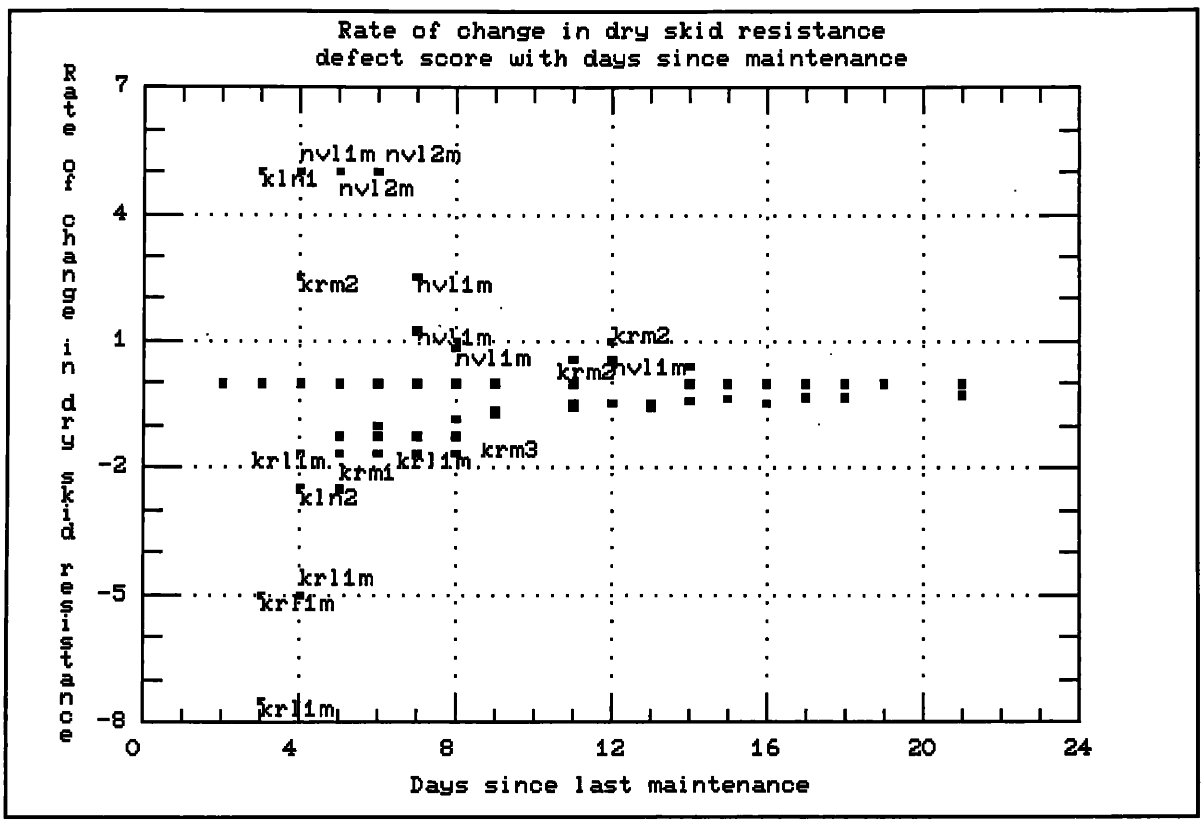

Figure 11 Rate of change of dry skid resistance defect score with days since last maintenance.

APPENDIX H

RESULTS OF ACCEPTABILITY CRITERIA ASSESSMENT

H-2

Contents

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Haul Roads Research Project

Functional performance assessment questionnaire

Introduction

Functional design aspects refer to the ability of a 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 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 a safety or cost-benefit analysis of proposed betterment activities.

The principal objectives of this questionnaire are:

- To generate data which can be used to develop functional performance related specifications for wearing course materials
- To obtain data which can be used to list priorities for maintenance and betterment activities.

The series of questions and evaluations attached on the following sheets are designed to assess the functional performance of a haul road both in terms of acceptable functional performance levels and the effect of performance deficiencies on a truck, its tyres and the productivity of the whole transport operation. Your response to these questions should be based on your overall familiarity with surface mining and perceptions about haul road functionality and the relationship between the haulage system and safe and economic mining operations.

There are two basic areas to be evaluated by the questionnaire;

1. Road user assessment of desirable and unacceptable characteristic performance limits and
2. The impact of functionality on the economics and safety of the operation.

Instructions

1 Road User Assessment of Desirable and Unacceptable Characteristic performance Limits.

Road user assessment of performance criteria is based on a classification of degree and extent for each functional characteristic of the road. Road defect upper limits are specified for desirability, together with a threshold of unacceptability. The level of functional performance of a haul road may be determined by considering those characteristics which combine to control functionality, eg. dustiness, potholes, skid resistance, etc. The extent and degree of severity of each of these characteristics may be assessed according to a five point scale as given in Table 1 and 2. Using your experience, consider each defect in a broad sense as it applies to the haul road (NOT ramp or tip areas). Using the detailed descriptions of the degree of a particular defect and extent (Table 1 and 2), complete the performance evaluation form for desirable and unacceptable levels of performance.

For example, for the characteristic of dustiness, you may decide desirable degree is ≤ 2 and extent ≤ 3. Unacceptable levels may be degree ≥ 4 and extent ≥ 3. Enter these values in the evaluation form as shown overleaf.

CHARACTERISTIC	DESIRABLE		UNACCEPTABLE		COMMENTS
	DEGREE	EXTENT	DEGREE	EXTENT	
Dustiness	2	3	4	3	

TABLE 1 **Classification of the Degree of Haul Road Aspects to be Evaluated.**

CHARACTERISTIC	DESCRIPTION				
	Degree 1	Degree 2	Degree 3	Degree 4	Degree 5
Potholes	Surface is pock marked , holes < 50mm diameter.	Potholes 50-100mm diameter.	Potholes 100-400mm diameter and influence riding quality.	Potholes 400-800mm diameter, influence riding quality and obviously avoided by most vehicles.	Potholes >800mm diameter, influence riding quality and require speed reduction or total avoidance.
Corrugations	Slight corrugations, difficult to feel in light vehicle.	Corrugations present and noticeable in light vehicle.	Corrugations very visible and reduce riding quality noticeably.	Corrugations noticeable in haul truck and causing driver to reduce speed.	Corrugations noticeable in haul truck and causing driver to reduce speed significantly.
Rutting	Difficult to discern unaided, <20mm.	Just discernable with eye, 20-50mm.	Discernable, 50-80mm.	Obvious from moving vehicle, >80mm.	Severe, affects direction stability of vehicle.
Loose material	Very little loose material on road, <5mm depth.	Small amount of loose material on road to a depth of 5-10mm.	Loose material present on road to a depth of 10-20mm.	Significant loose material on road to a depth of 20-40mm.	Considerable loose material, depth >40mm.
Dustiness	Dust just visible behind vehicle.	Dust visible, no oncoming vehicle driver discomfort, good visibility.	Notable amount of dust, windows closed in oncoming vehicle, visibility just acceptable, overtaking difficult.	Significant amount of dust, window closed in oncoming vehicle, visibility poor.	Very dusty, surroundings obscured to a dangerous level.
Stoniness - fixed in wearing course	Some protruding stones, but barely felt or heard when travelling in light vehicle.	Protruding stones felt and heard in light vehicle.	Protruding stones influence riding quality in light vehicle but still acceptable.	Protruding stones occasionally require evasive action of light vehicle.	Protruding stones require evasive action of haul truck.
Stoniness - loose on road	Occasional loose stone (<75mm diameter), <2/m^2	Some loose stone, 2-4/m^2	Loose stone 4-6/m^2, occasional discomfort felt.	Considerable loose stone on surface, >6/m^2, reducing riding quality.	Large amounts of loose stone causing significant reduction in riding quality.
Cracks - longitudinal	Faint cracks discernable when surface cleaned.	Distinct, mostly closed, easily discernable when walking.	Distinct, mostly open, discernable from vehicle.	Open cracks, >3mm separation <u>or</u> wide open cracks >10mm separation, in travelling lanes.	Extensive open cracks, >3mm separation together with secondary cracks <u>or</u> extensive wide

TABLE 1 **Classification of the Degree of Haul Road Aspects to be Evaluated (cont'd).**

CHARACTERISTIC	DESCRIPTION				
	Degree 1	Degree 2	Degree 3	Degree 4	Degree 5
Cracks - slip	Faint cracks discernable when surface cleaned.	Distinct, mostly closed, easily discernable when walking.	Distinct, mostly open, discernable from vehicle.	Open cracks, >3mm separation or wide open cracks >10mm separation, in travelling lanes.	Extensive open cracks, >3mm separation together with secondary cracks or extensive wide open cracks >10mm separation, in travelling lanes.
Cracks - crocodile	Very faint cracks in wheel path.	Faint cracks discernable when walking, closed.	Distinct cracks upto 2mm wide, no apparent deformation.	Open cracks (>2mm) with some deformation and/or spalling of cracked areas.	Open cracks with severe deformation and/or spalling of edges.
Skid resistance - wet	Wearing course material of good quality, road properly cambered, little loose material present.	Wearing course strength and PI acceptable, road cambered, loose material acceptable.	Wearing course strength low, PI fairly high, unsatisfactory camber and loose material.	Wearing course strength low, PI high, water standing on surface when raining, loose material influences skid resistance significantly.	Wearing course strength very low, PI very high, road very slippery when wet, loose material reduces skid resistance unacceptably.
Skid resistance - dry	Wearing course material of good quality, road properly cambered, little loose material present.	Wearing course strength and PI acceptable, road cambered, loose material acceptable.	Wearing course strength low, PI fairly high, unsatisfactory camber and loose material.	Wearing course strength low, PI high, loose material influences skid resistance significantly.	Wearing course strength very low, PI very high, loose material reduces skid resistance unacceptably.
Drainage on road	Very little water accumulates on road, no surface erosion is evident.	Shallow depressions may retain water for a limited time, most water drains away rapidly.	water may be retained in ruts and potholes, some surface erosion evident.	Water retained over a significant portion of the road, surface erosion <50mm deep in channels.	Water ponding on road to depths >50mm and erosion channels deeper than 50mm.
Drainage at roadside	Side drains very effective, well shaped with no obstructions.	Slightly irregular, some loose debris or occasional erosion, road well above side drain level.	Drains irregular in shape, blocked or eroded, road above side drain level.	Drains irregular or eroded and blocked over >25% road length, road and side drain at same elevation.	Side drains deeply eroded or non existent along 75% of road length or road surface below side drain.

NOTE. 1. Description of degrees refers to haul truck unless otherwise stated.
2. Rutting - depressions extended in length and limited in width, usually occurring in a longitudinal direction and in the wheel path.
3. Corrugations - regularly spaced transverse undulations of the pavement at regular intervals less than 1m apart.
4. Crocodile cracks - fine irregular cracks in the wheel path resembling crocodile skin.

TABLE 2 **Classification of the Extent of Haul Road Aspects to be Evaluated.**

EXTENT	DESCRIPTION
1	Isolated occurrence, less than 5% of road affected.
2	Intermittent occurrence, between 5-15% of road affected.
3	Regular occurrence, between 16-30% of road affected.
4	Frequent occurrence, between 31-60% of road affected.
5	Extensive occurrence, more than 60% of the road affected.

HAUL ROAD FUNCTIONAL PERFORMANCE EVALUATION FORM 1

NAME OF THE MINE? ....
HOW LONG HAVE YOU BEEN ASSOCIATED WITH SURFACE MINING? .... Years

CHARACTERISTIC	DESIRABLE		UNACCEPTABLE		COMMENTS
	DEGREE	EXTENT	DEGREE	EXTENT	
Potholes					
Corrugations					
Rutting					
Loose material					
Dustiness					
Stoniness - fixed in wearing course					
Stoniness - loose on road					
Cracks - longitudinal					
Cracks - slip					
Cracks - crocodile					
Skid resistance - wet		*		*	
Skid resistance - dry		*		*	
Drainage on road		*		*	
Drainage at roadside		*		*	
* Do not record extent for these functional aspects					

2 The impact of Functionality on the Economics and Safety of the Operation.

The economic impact is quantified by first deciding if a given condition or characteristic can affect either the truck, the tyres or the operation's productivity. If any of these three items are affected, the degree to which this occurs is scored using the attached rating system. The safety impact is estimated by scoring the accident potential of each condition and characteristic. Accident potential assigns a subjective probability to every condition and characteristic. An accident in this case is defined as an unplanned event which results in operator injury or equipment damage.

Consider each item in a broad sense, ie., scoring in terms of its impact on average or typical daily operating conditions on the haul road (NOT ramp or tip areas). For example, whilst a dust problem on the road may lead to vehicle collisions, is this typical? The typical situation is a dust problem reducing visibility and vehicle speed, hence increasing cycle time. The procedure is outlined below.

STEP 1 Review each item on the scoring sheet and decide whether it affects the operation, truck or tyre. Mark appropriate box(es).

STEP 2 For each condition identified with a mark (step 1), score its expected impact during a year of production using the IMPACT RANKING SCALE, Table 3.

STEP 3 Based on your experience, evaluate the possibility that each item on the scoring sheet could cause an accident, using the ACCIDENT RANKING SCALE, Table 4.

A typical entry in the assessment form is shown below, for the pothole characteristic.

FUNCTIONAL DESIGN CHARACTERISTIC	ITEM AFFECTED BY CHARACTERISTIC			IMPACT RANKING SCORE			ACCIDENT POTENTIAL SCORE
	Operation	Truck	Tyre	Operation	Truck	Tyre	
Potholes	✓	✓	✓	2	2	3	1

Table 3 Impact Ranking Scale

ITEM	IMPACT SCORE	DESCRIPTION
TRUCK		
	0	No mechanical damage
	1	Minor mechanical damage, downtime < 1 shift, low potential for premature component failure.
	2	Minor mechanical damage, downtime < 1 shift, medium potential for premature component failure.
	3	Mechanical damage, downtime < 1 week, high potential for premature component failure.
	4	Mechanical damage, downtime < 1 month.
	5	Mechanical damage, downtime > 1 month.
OPERATION		
	0	< 1% slow down.
	1	1-5% slow down.
	2	6-10% slow down.
	3	11-15% slow down.
	4	>15% slow down.
	5	Production stops.
TYRES		
	0	No impact on tyre wear.
	1	Tyre wear increased by 5%.
	2	Tyre wear increased by 10%, low potential for cuts.
	3	Tyre wear increased by 25%, medium potential for cuts.
	4	Tyre wear increased by 50%, high potential for cuts.
	5	Tyre wear increased by >50%, high potential for cuts.

Table 4 Accident potential scale

ACCIDENT POTENTIAL SCORE	DESCRIPTION
0	Could cause an accident resulting in operator injury or equipment damage but probability is low (P<1%).
1	P 1-5%
2	P 6-10%
3	P 11-20%
4	P 21-30%
5	P 31-42%
6	P 43-54%
7	P 55-66%
8	P 67-78%
9	P 79-90%
10	Very high probability of accident. If situation is left uncorrected, accident involving equipment damage or operator injury will almost certainly occur (P>90%)

SCORING SHEET - FUNCTIONAL PERFORMANCE ASSESSMENT FORM 2

FUNCTIONAL DESIGN CHARACTERISTIC	ITEM AFFECTED BY CHARACTERISTIC			IMPACT RANKING SCORE			ACCIDENT POTENTIAL SCORE	COMMENTS
	Operation	Truck	Tyre	Operation	Truck	Tyre		
Potholes								
Corrugations								
Rutting								
Loose material								
Dustiness								
Stoniness - fixed in wearing course								
Stoniness - loose on road								

Continued on next page...

SCORING SHEET - FUNCTIONAL PERFORMANCE ASSESSMENT FORM 2 (cont'd)

FUNCTIONAL DESIGN CHARACTERISTIC	ITEM AFFECTED BY CHARACTERISTIC			IMPACT RANKING SCORE			ACCIDENT POTENTIAL SCORE	COMMENTS
	Operation	Truck	Tyre	Operation	Truck	Tyre		
Cracks - longitudinal								
Cracks - slip								
Cracks - Crocodile								
Skid resistance - wet								
Skid resistance - dry								
Drainage on road								
Drainage at roadside								

CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Mine
YEARS EXPERIENCE	2.5

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	1	1	2	3	3	2	1	3
Corrugations	1	2	3	3	3	2	2	4
Rutting	2	3	4	4	0	2	1	2
Loose material	1	2	2	2	2	1	3	5
Dustiness	1	2	4	3	3	0		4
Stoniness - fixed	2	3	4	3	2	1	4	2
Stoniness - loose	1	2	3	2	3	1	3	5
Cracks - longitudinal	1	2	4	2			1	0
Cracks - slip	1	2	3	3				
Cracks - crocodile	2	3	4	4				
Skid resistance wet	2		3		4			5
Skid resistance dry	2		3		3		1	4
Drainage on road	1		3		4			3
Drainage side of road	2		4		2			3

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CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Manuf
YEARS EXPERIENCE	17

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	1	3	3	4	2	2	2	1
Corrugations	1	5	4	4	2	3	3	1
Rutting	2	4	3	3	1	2	2	1
Loose material	1	5	4	4		0	1	2
Dustiness	2	4	3	4	3			4
Stoniness - fixed	2	3	4	4	1	1	2	1
Stoniness - loose	2	1	4	4		0	2	1
Cracks - longitudinal	2	2	3	3		1	1	1
Cracks - slip	2	2	3	3		1	1	1
Cracks - crocodile	2	2	3	3		1	1	1
Skid resistance wet	2		3		3		2	3
Skid resistance dry	2		3		2		2	3
Drainage on road	2		4		1		3	2
Drainage side of road	2		3		1		1	1

CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Manuf
YEARS EXPERIENCE	15

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	2	2	3	2	1	1	1	2
Corrugations	2	3	2	3	2	2	3	2
Rutting	3	3	4	4	1	1	1	1
Loose material	3	4	4	3	1	0	1	1
Dustiness	2	2	3	4	2	0		2
Stoniness - fixed	3	4	3	5		0	0	0
Stoniness - loose	2	3	3	4	0	1	1	2
Cracks - longitudinal	2	3	3	3				
Cracks - slip	2	3	3	3				
Cracks - crocodile	2	3	3	3				
Skid resistance wet	2		3		4	4		6
Skid resistance dry	3		3		2	2	2	6
Drainage on road	2		3		1	0		0
Drainage side of road	2		3		1			3

CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Manuf
YEARS EXPERIENCE	30

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	3	2	3	3	2	2	2	1
Corrugations	3	2	3	3	2	2	2	2
Rutting	3	3	3	3			1	3
Loose material	3	4	4	4	2			2
Dustiness	2	3	3	3	1	1		4
Stoniness - fixed	4	3	4	3			3	2
Stoniness - loose	1	3	3	3			3	2
Cracks - longitudinal	3	3	4	4				1
Cracks - slip	4	4	5	4				1
Cracks - crocodile	4	4	4	4				1
Skid resistance wet	3		3		3	2	3	7
Skid resistance dry	3		3		3	2	3	7
Drainage on road	3		4		2		4	5
Drainage side of road	1		3		2		2	4

CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Mine
YEARS EXPERIENCE	6

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	2	2	3	3	3	1	1	2
Corrugations	1	2	3	3	2	2		2
Rutting	2	2	3	3	2	2		2
Loose material	2	2	3	3			0	2
Dustiness	2	2	3	3	3			10
Stoniness - fixed	1	2	4	3		1	0	2
Stoniness - loose	2	2	3	3	3	1	2	1
Cracks - longitudinal	2	2	3	3		2	2	2
Cracks - slip	2	2	3	3		2	2	2
Cracks - crocodile	2	2	4	3		2	2	2
Skid resistance wet	1		3		2		2	8
Skid resistance dry	1		3		2		2	4
Drainage on road	1		3		2		2	3
Drainage side of road	2		3		3		2	3

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CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Mine
YEARS EXPERIENCE	15

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	1	2	3	5	1		1	0
Corrugations	1	2	3	5	1		1	0
Rutting	2	3	4	5	1		1	0
Loose material	1	2	3	5	4		4	4
Dustiness	1	3	4	5	4		2	4
Stoniness - fixed	1	3	4	5	4		1	1
Stoniness - loose	1	3	4	5	4		1	2
Cracks - longitudinal	1	3	4	5	2	2	2	2
Cracks - slip	1	3	4	5	2	3	2	2
Cracks - crocodile	1	3	4	5	2		1	1
Skid resistance wet	2		3		1		2	2
Skid resistance dry	2		3		3			3
Drainage on road	2		3		1	1	2	2
Drainage side of road	2		3		2	1	2	3

CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Mine
YEARS EXPERIENCE	6

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	2	2	4	4	1	2	1	0
Corrugations	2	2	3	4	2	1	1	1
Rutting	3	2	4	3	0	0	1	0
Loose material	1	2	3	3	3			4
Dustiness	2	2	3	3	1			4
Stoniness - fixed	3	2	4	4			2	0
Stoniness - loose	3	2	4	4	1		1	0
Cracks - longitudinal	3	2	4	4			1	0
Cracks - slip	3	2	4	4			1	0
Cracks - crocodile	3	3	5	4	0		0	0
Skid resistance wet	2		3		4			4
Skid resistance dry	2		3		1			1
Drainage on road	2		4		2		1	1
Drainage side of road	2		3		1			1

CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Mine
YEARS EXPERIENCE	5

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	2	2	3	3	2	2	1	1
Corrugations	2	3	3	5	2	2	1	1
Rutting	3	2	4	3	2			1
Loose material	1	1	1	1	2		3	5
Dustiness	2	1	2	1	4			5
Stoniness - fixed	1	1	2	2	2		3	2
Stoniness - loose	1	1	1	1	2			2
Cracks - longitudinal	2	3	2	4	2			1
Cracks - slip	3	4	4	5	2	3	3	3
Cracks - crocodile	3	3	4	4	2		2	2
Skid resistance wet	2		4		5	5		5
Skid resistance dry	1		3		1	5	5	3
Drainage on road	1		2		5			5
Drainage side of road	1		2		3	2	3	1

CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Mine
YEARS EXPERIENCE	9

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	1	2	3	2	3	1	2	2
Corrugations	1	2	3	2	2	1	2	2
Rutting	1	2	3	2	3	2	2	3
Loose material	1	2	3	2	5	2	2	4
Dustiness	1	2	3	2	6	1	1	6
Stoniness - fixed	1	2	3	2				
Stoniness - loose	1	2	3	2	3	1	1	2
Cracks - longitudinal	1	2	3	2	1	1	2	1
Cracks - slip	1	2	3	2	1	3	2	3
Cracks - crocodile	1	2	3	2	2	2	3	3
Skid resistance wet	1		3		5	4	2	6
Skid resistance dry	1		3		6	6	2	6
Drainage on road	2		3		6	1	2	4
Drainage side of road	1		3		1	1	1	3

CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Mine
YEARS EXPERIENCE	3

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	1	2	3	4	4	3	3	3
Corrugations	1	2	3	4	2	2	2	0
Rutting	2	3	3	4	2		2	0
Loose material	1	2	3	4	3		4	2
Dustiness	1	3	3	4	4	0		10
Stoniness - fixed	2	3	3	4	2		2	0
Stoniness - loose	1	2	3	3	3		2	2
Cracks - longitudinal	2	3	3	4			0	0
Cracks - slip	2	3	4	4			0	0
Cracks - crocodile	3	3	3	4			0	0
Skid resistance wet	1		2		4		1	5
Skid resistance dry	1		3		2			0
Drainage on road	1		3		2		1	4
Drainage side of road	1		3		4			6

CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Mine
YEARS EXPERIENCE	20

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	2	3	4	4	3	2	3	1
Corrugations	2	3	3	3	2	2	2	1
Rutting	2	2	3	3	2			
Loose material	2	3	4	3	1			
Dustiness	2	3	4	3	5			10
Stoniness - fixed	2	3	4	3	2		2	
Stoniness - loose	2	2	3	3	3		2	2
Cracks - longitudinal	1	2	3	2				
Cracks - slip	1	2	4	3				
Cracks - crocodile	1	2	4	3				
Skid resistance wet	1		2		4		1	3
Skid resistance dry	1		2					
Drainage on road	2		3		2		1	4
Drainage side of road	2		3		3			7

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CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Mine
YEARS EXPERIENCE	11

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	1	2	3	3	1	1	2	1
Corrugations	1	1	2	3	3	3	1	2
Rutting	1	1	2	2	4	3	4	2
Loose material	1	1	2	3	1	0	4	3
Dustiness	1	3	4	4	3	3		4
Stoniness - fixed	1	1	2	1	3	3	4	2
Stoniness - loose	1	1	2	2	1	1	4	3
Cracks - longitudinal	5	1	5	3				
Cracks - slip	5	1	5	3				
Cracks - crocodile	5	1	5	3				
Skid resistance wet	2		3		2	2	3	3
Skid resistance dry	2		3		2	2	3	3
Drainage on road	1		3		2		1	1
Drainage side of road	1		3		1	1	1	1

CRITICAL FUNCTIONAL PERFORMANCE EVALUATION

RESPONDENT	Mine
YEARS EXPERIENCE	29

	Desirable		Unacceptable		Impact ranking score			Accident
	Degree	Extent	Degree	Extent	Operation	Truck	Tyre	Pot score
Potholes	1	2	3	3	1	1	2	1
Corrugations	1	1	2	3	3	3	1	2
Rutting	1	1	2	2	4	3	4	2
Loose material	1	1	2	3	1	0	4	3
Dustiness	1	3	4	4	3	3		4
Stoniness - fixed	1	1	3	3	3	3	4	2
Stoniness - loose	1	1	2	2	1	1	4	3
Cracks - longitudinal	3	2	3	4				
Cracks - slip	3	2	3	4				
Cracks - crocodile	3	2	3	4				
Skid resistance wet	2		3		2	2	3	3
Skid resistance dry	2		3		2	2	3	3
Drainage on road	1		3		2		2	1
Drainage side of road	1		3		1	1	1	1

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SUMMARY OF FUNCTIONAL QUESTIONNAIRE RESPONSES

Limits of acceptability for functional performance

	Acceptable		Unacceptable			
	Average Degree	Average Extent	Average Degree	Average Extent	Average Desirable	Average Undesirable
Potholes	1.5	2.1	3.1	3.3	3.2	10.2
Corrugations	1.5	2.3	2.8	3.5	3.4	9.9
Rutting	2.1	2.4	3.2	3.2	5.0	10.2
Loose material	1.5	2.4	2.9	3.1	3.5	9.0
Dustiness	1.5	2.5	3.3	3.3	3.9	10.9
Stoniness - fixed	1.8	2.4	3.4	3.2	4.4	10.9
Stoniness - loose	1.5	1.9	2.9	2.9	2.8	8.5
Cracks - longitudinal	2.2	2.3	3.4	3.3	5.0	11.2
Cracks - slip	2.3	2.5	3.7	3.5	5.7	13.1
Cracks - crocodile	2.5	2.5	3.8	3.5	6.2	13.3
Skid resistance wet	1.8		2.9		8.8	14.6
Skid resistance dry	1.8		2.9		8.8	14.6
Drainage on road	1.6		3.2		8.1	15.8
Drainage side of road	1.5		3.0		7.7	15.0

SUMMARY OF FUNCTIONAL QUESTIONNAIRE RESPONSES

Impact of functionality on safety

	Percent responses identifying impact			Average impact score			Weighted ID x impact			Percent responses identifying AP	Average AP	Weighted average AP
	Operation	Truck	Tyres	Operation	Truck	Tyres	Operation	Truck	Tyres			
Potholes	100.0	92.3	100.0	2.1	1.7	1.3	2.1	1.5	1.3	100.0	1.4	1.4
Corrugations	100.0	92.3	92.3	2.2	2.1	1.9	2.2	1.9	1.7	100.0	1.5	1.5
Rutting	92.3	61.5	76.9	1.8	1.9	1.3	1.7	1.2	1.0	84.6	1.5	1.2
Loose material	84.6	46.2	76.9	2.3	0.5	2.0	1.9	0.2	1.5	92.3	2.9	2.7
Dustiness	100.0	53.8	15.4	3.2	1.1	1.5	3.2	0.6	0.2	92.3	5.5	5.1
Stoniness - fixed	61.5	46.2	92.3	2.4	1.5	1.9	1.5	0.7	1.7	84.6	1.4	1.2
Stoniness - loose	84.6	53.8	92.3	2.2	0.9	1.8	1.8	0.5	1.6	92.3	2.1	1.9
Cracks - longitudinal	23.1	30.8	53.8	1.7	1.5	1.5	0.4	0.5	0.8	61.5	0.9	0.5
Cracks - slip	23.1	38.5	53.8	1.7	2.4	1.8	0.4	0.9	1.0	61.5	1.5	0.9
Cracks - crocodile	30.8	23.1	53.8	1.5	1.7	1.5	0.5	0.4	0.8	61.5	1.3	0.8
Skid resistance wet	100.0	46.2	69.2	3.3	3.2	2.2	3.3	1.5	1.5	92.3	4.6	4.2
Skid resistance dry	92.3	46.2	69.2	2.4	3.2	2.4	2.2	1.5	1.7	92.3	3.8	3.5
Drainage on road	100.0	23.1	76.9	2.5	0.7	2.3	2.5	0.2	1.8	92.3	2.5	2.3
Drainage side of road	100.0	38.5	61.5	1.9	1.2	1.8	1.9	0.5	1.1	100.0	3.0	3.0

APPENDIX I

PERFORMANCE RANKING OF SITES AND CRITICAL DEFECTS

I-2

Contents

Tabulations of material property variation with functional performance ranking for defects analysed.

Defect functional performance classification with respect to TRH20

MATERIAL PARAMETER VARIATION WITH FUNCTIONAL PERFORMANCE RANKING OVERALL UNWEIGHTED FUNCTIONAL PERFORMANCE						
PERFORMANCE RANKING	DR	LL	PI	PL	GC	SP
B2	0.4	21.0	4.0	17.0	30.1	82.0
B2	0.4	17.0	5.0	12.0	31.1	90.0
B2	0.6	23.0	8.0	15.0	21.3	196.0
B2	0.5	24.0	8.0	16.0	28.7	128.0
B2	0.4	18.0	4.0	14.0	24.8	102.0
B2	0.5	21.0	6.0	15.0	30.7	111.0
Average	*(0.5)*	*(20.7)*	*(5.8)*	*(14.8)*	*(27.8)*	*(118.2)*
C1	0.6	24.0	8.0	16.0	30.9	160.0
C1	0.6	24.0	10.0	14.0	36.3	198.0
C1	0.4	22.0	5.0	17.0	26.2	72.0
C1	0.6	23.0	7.0	16.0	28.8	164.5
C1	0.5	22.0	7.0	15.0	27.7	178.5
Average	*(0.5)*	*(23.0)*	*(7.4)*	*(15.6)*	*(30.0)*	*(154.6)*

MATERIAL PARAMETER VARIATION WITH FUNCTIONAL PERFORMANCE RANKING OVERALL WEIGHTED FUNCTIONAL PERFORMANCE						
PERFORMANCE RANKING	DR	LL	PI	PL	GC	SP
B2	0.4	21.0	4.0	17.0	30.1	82.0
B2	0.4	17.0	5.0	12.0	31.1	90.0
B2	0.4	18.0	4.0	14.0	24.8	102.0
B2	0.5	24.0	8.0	16.0	28.7	128.0
Average	*(0.4)*	*(20.0)*	*(5.3)*	*(14.8)*	*(28.7)*	*(100.5)*
C1	0.6	24.0	8.0	16.0	30.9	160.0
C1	0.4	22.0	5.0	17.0	26.2	72.0
C1	0.5	21.0	6.0	15.0	30.7	111.0
C1	0.6	24.0	10.0	14.0	36.3	198.0
C1	0.6	23.0	8.0	15.0	21.3	196.0
C1	0.6	23.0	7.0	16.0	28.8	164.5
C1	0.5	22.0	7.0	15.0	27.7	178.5
Average	*(0.5)*	*(22.7)*	*(7.3)*	*(15.4)*	*(28.8)*	*(154.3)*

MATERIAL PROPERTY VARIATION WITH FUNCTIONAL PERFORMANCE RANKING FOR CORRUGATION DEFECT

PERFORMANCE RANKING	DR	LL	PI	PL	GC	SP
A	0.4	21.0	4.0	17.0	30.1	82.0
A	0.5	21.0	6.0	15.0	30.7	111.0
A	0.6	24.0	8.0	16.0	30.9	160.0
A	0.4	18.0	4.0	14.0	24.8	102.0
A	0.5	24.0	8.0	16.0	28.7	128.0
A	0.6	23.0	8.0	15.0	21.3	196.0
A	0.6	24.0	10.0	14.0	36.3	198.0
A	0.6	23.0	7.0	16.0	28.8	164.5
A	0.5	22.0	7.0	15.0	27.7	178.5
Average	*(0.5)*	*(22.2)*	*(6.9)*	*(15.3)*	*(28.8)*	*(146.7)*
B1	0.4	17.0	5.0	12.0	31.1	90.0
Average	*(0.4)*	*(17.0)*	*(5.0)*	*(12.0)*	*(31.1)*	*(90.0)*
B2	0.4	22.0	5.0	17.0	26.2	72.0
Average	*(0.4)*	*(22.0)*	*(5.0)*	*(17.0)*	*(26.2)*	*(72.0)*

MATERIAL PROPERTY VARIATION WITH FUNCTIONAL PERFORMANCE RANKING FOR LOOSE MATERIAL DEFECT

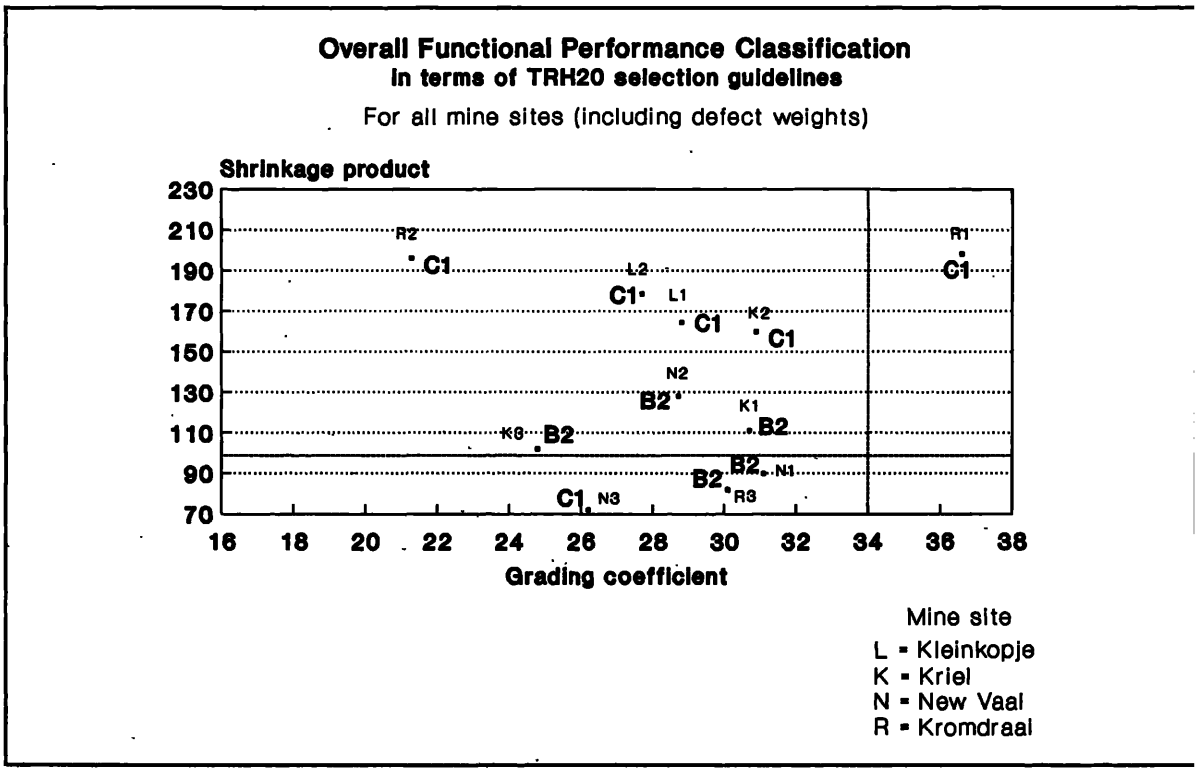
PERFORMANCE RANKING	DR	LL	PI	PL	GC	SP
B1	0.5	24.0	8.0	16.0	28.7	128.0
Average	*(0.5)*	*(24.0)*	*(8.0)*	*(16.0)*	*(28.7)*	*(128.0)*
B2	0.6	23.0	8.0	15.0	21.3	196.0
B2	0.5	21.0	6.0	15.0	30.7	111.0
B2	0.4	18.0	4.0	14.0	24.8	102.0
B2	0.6	24.0	8.0	16.0	30.9	160.0
B2	0.6	23.0	7.0	16.0	28.8	164.5
B2	0.4	17.0	5.0	12.0	31.1	90.0
Average	*(0.5)*	*(21.0)*	*(6.3)*	*(14.7)*	*(27.9)*	*(137.3)*
C1	0.4	21.0	4.0	17.0	30.1	82.0
C1	0.4	22.0	5.0	17.0	26.2	72.0
C1	0.6	24.0	10.0	14.0	36.3	198.0
C1	0.5	22.0	7.0	15.0	27.7	178.5
Average	*(0.5)*	*(22.3)*	*(6.5)*	*(15.8)*	*(30.1)*	*(132.6)*

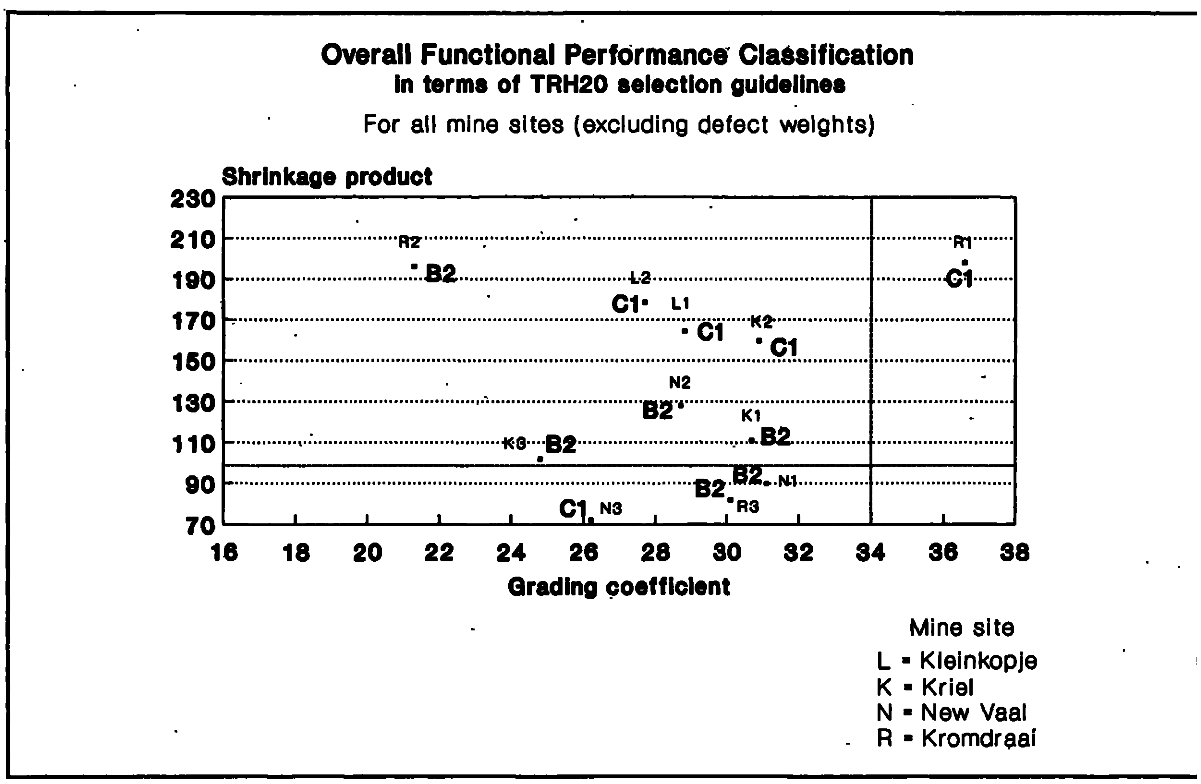
MATERIAL PROPERTY VARIATION WITH FUNCTIONAL PERFORMANCE RANKING FOR DUSTINESS DEFECT						
PERFORMANCE RANKING	DR	LL	PI	PL	GC	SP
B2	0.4	21.0	4.0	17.0	30.1	82.0
B2	0.4	17.0	5.0	12.0	31.1	90.0
B2	0.4	18.0	4.0	14.0	24.8	102.0
B2	0.5	24.0	8.0	16.0	28.7	128.0
Average	*(0.4)*	*(20.0)*	*(5.3)*	*(14.8)*	*(28.7)*	*(100.5)*
C1	0.6	24.0	8.0	16.0	30.9	160.0
C1	0.5	21.0	6.0	15.0	30.7	111.0
C1	0.6	23.0	8.0	15.0	21.3	196.0
C1	0.6	24.0	10.0	14.0	36.3	198.0
Average	*(0.6)*	*(23.0)*	*(8.0)*	*(15.0)*	*(29.8)*	*(166.3)*
C2	0.4	22.0	5.0	17.0	26.2	72.0
C2	0.6	23.0	7.0	16.0	28.8	164.5
C2	0.5	22.0	7.0	15.0	27.7	178.5
Average	*(0.5)*	*(22.3)*	*(6.3)*	*(16.0)*	*(27.6)*	*(138.3)*

MATERIAL PROPERTY VARIATION WITH FUNCTIONAL PERFORMANCE RANKING FOR LOOSE STONINESS DEFECT						
PERFORMANCE RANKING	DR	LL	PI	PL	GC	SP
A	0.4	21.0	4.0	17.0	30.1	82.0
A	0.4	17.0	5.0	12.0	31.1	90.0
Average	*(0.4)*	*(19.0)*	*(4.5)*	*(14.5)*	*(30.6)*	*(86.0)*
B1	0.5	21.0	6.0	15.0	30.7	111.0
B1	0.5	24.0	8.0	16.0	28.7	128.0
B1	0.6	23.0	7.0	16.0	28.8	164.5
B1	0.6	24.0	10.0	14.0	36.3	198.0
B1	0.4	18.0	4.0	14.0	24.8	102.0
Average	*(0.5)*	*(22.0)*	*(7.0)*	*(15.0)*	*(29.9)*	*(140.7)*
B2	0.6	24.0	8.0	16.0	30.9	160.0
B2	0.4	22.0	5.0	17.0	26.2	72.0
B2	0.6	23.0	8.0	15.0	21.3	196.0
Average	*(0.5)*	*(23.0)*	*(7.0)*	*(16.0)*	*(26.2)*	*(142.7)*
C1	0.5	22.0	7.0	15.0	27.7	178.5
Average	*(0.5)*	*(22.0)*	*(7.0)*	*(15.0)*	*(27.7)*	*(178.5)*

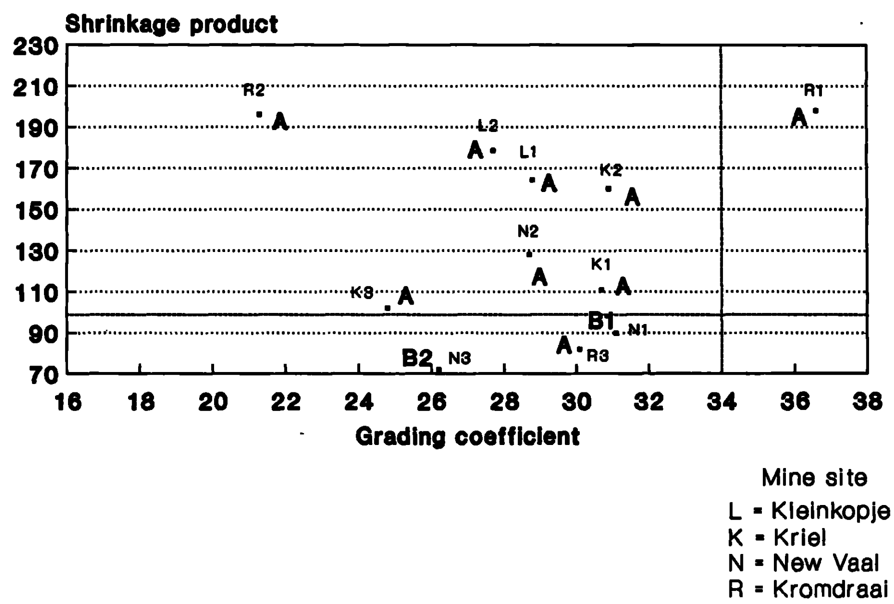
MATERIAL PROPERTY VARIATION WITH FUNCTIONAL PERFORMANCE RANKING FOR WET SKID RESISTANCE DEFECT						
PERFORMANCE RANKING	**DR**	**LL**	**PI**	**PL**	**GC**	**SP**
B2	0.4	21.0	4.0	17.0	30.1	82.0
B2	0.4	17.0	5.0	12.0	31.1	90.0
B2	0.4	18.0	4.0	14.0	24.8	102.0
B2	0.5	22.0	7.0	15.0	27.7	178.5
B2	0.4	22.0	5.0	17.0	26.2	72.0
B2	0.6	23.0	7.0	16.0	28.8	164.5
B2	0.6	23.0	8.0	15.0	21.3	196.0
B2	0.6	24.0	10.0	14.0	36.3	198.0
Average	*(0.5)*	*(21.3)*	*(6.3)*	*(15.0)*	*(28.3)*	*(135.4)*
C1	0.5	24.0	8.0	16.0	28.7	128.0
C1	0.5	21.0	6.0	15.0	30.7	111.0
Average	*(0.5)*	*(22.5)*	*(7.0)*	*(15.5)*	*(29.7)*	*(119.5)*
C2	0.6	24.0	8.0	16.0	30.9	160.0
Average	*(0.6)*	*(24.0)*	*(8.0)*	*(16.0)*	*(30.9)*	*(160.0)*

MATERIAL PROPERTY VARIATION WITH FUNCTIONAL PERFORMANCE RANKING FOR DRY SKID RESISTANCE DEFECT						
PERFORMANCE RANKING	**DR**	**LL**	**PI**	**PL**	**GC**	**SP**
B2	0.4	21.0	4.0	17.0	30.1	82.0
B2	0.4	17.0	5.0	12.0	31.1	90.0
B2	0.5	21.0	6.0	15.0	30.7	111.0
B2	0.4	18.0	4.0	14.0	24.8	102.0
B2	0.5	22.0	7.0	15.0	27.7	178.5
B2	0.6	23.0	7.0	16.0	28.8	164.5
B2	0.6	23.0	8.0	15.0	21.3	196.0
B2	0.5	24.0	8.0	16.0	28.7	128.0
Average	*(0.5)*	*(21.1)*	*(6.1)*	*(15.0)*	*(27.9)*	*(131.5)*
C1	0.6	24.0	8.0	16.0	30.9	160.0
C1	0.4	22.0	5.0	17.0	26.2	72.0
C1	0.6	24.0	10.0	14.0	36.3	198.0
Average	*(0.5)*	*(23.3)*	*(7.7)*	*(15.7)*	*(31.1)*	*(143.3)*

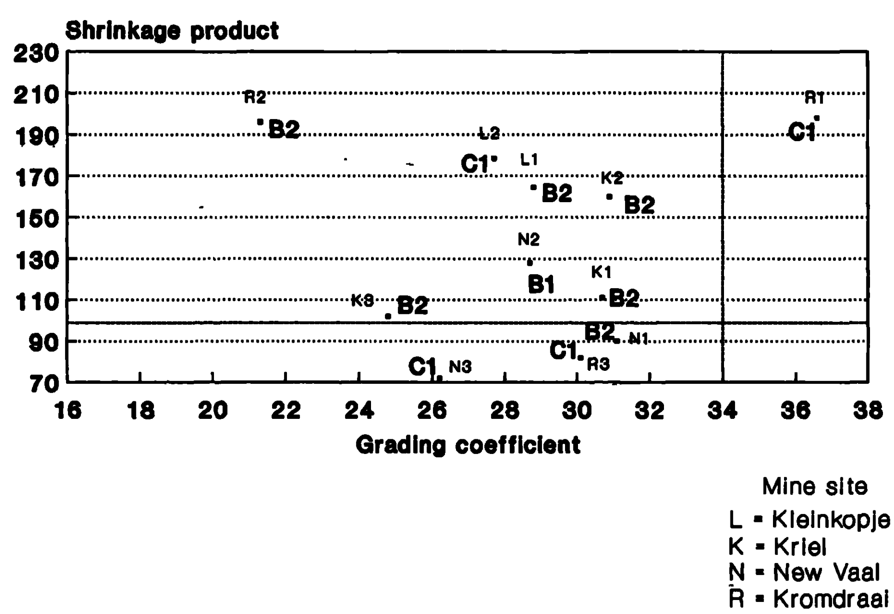

Overall Functional Performance Classification
In terms of TRH20 selection guidelines
For all mine sites (including defect weights)
Shrinkage product
Grading coefficient
Mine site
L - Kleinkopje
K - Kriel
N - New Vaal
R - Kromdraai


Overall Functional Performance Classification
In terms of TRH20 selection guidelines
For all mine sites (excluding defect weights)
Shrinkage product
Grading coefficient
Mine site
L - Kleinkopje
K - Kriel
N - New Vaal
R - Kromdraai

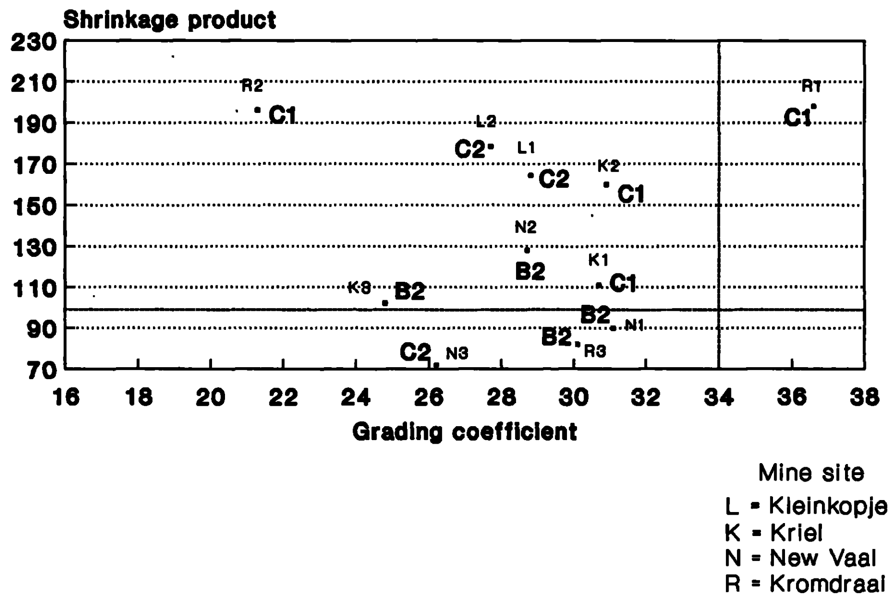
Corrugation Defect Functional Performance Classification
in terms of TRH20 selection guidelines



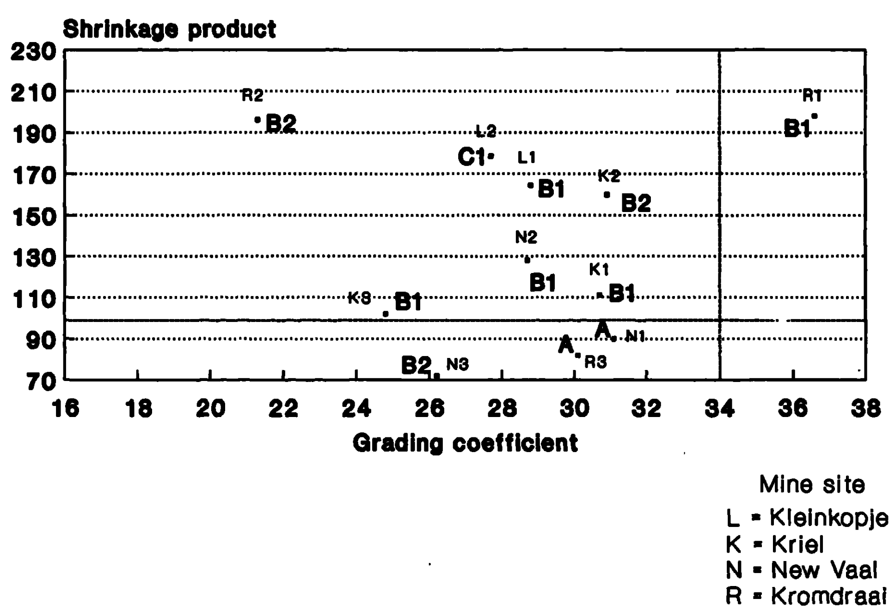
Loose Material Defect Functional Performance Classification
in terms of TRH20 selection guidelines



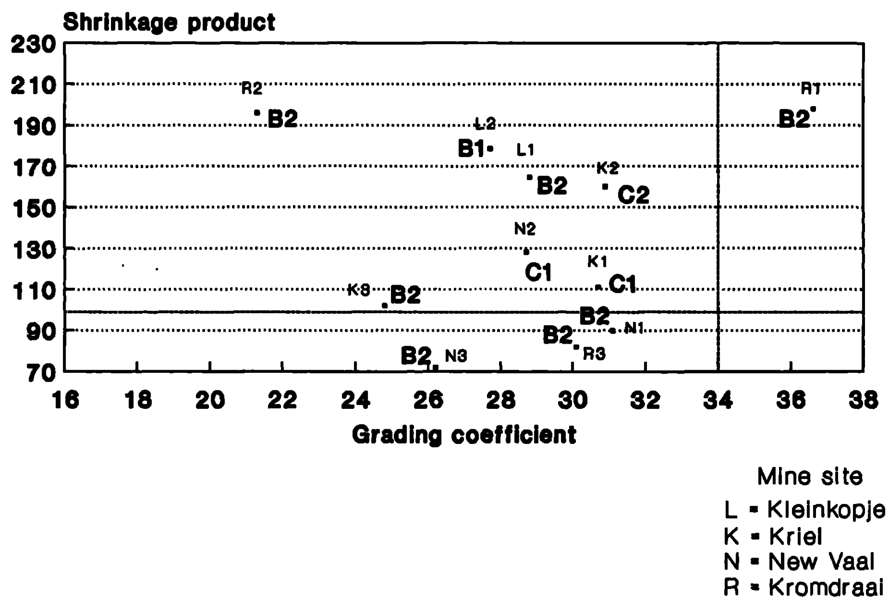
Dustiness Defect Functional Performance Classification
in terms of TRH20 selection guidelines



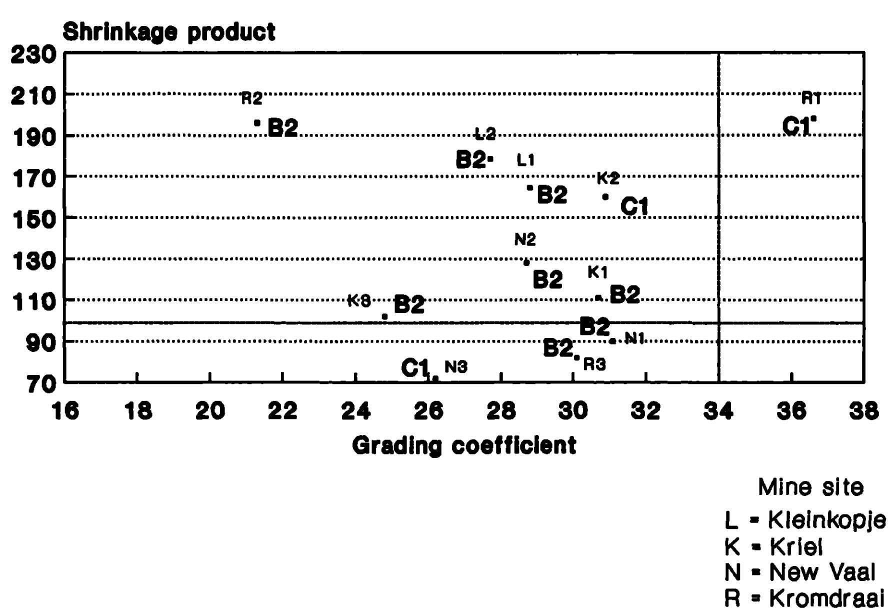
Loose Stoniness Defect Functional Performance Classification
in terms of TRH20 selection guidelines



Wet Skid Resistance Defect Functional Performance
Classification in terms of TRH20 selection guidelines



Dry Skid Resistance Defect Functional Performance
Classification in terms of TRH20 selection guidelines



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J1-1

APPENDIX J1

RESULTS OF HAUL ROAD IRI ROUGHNESS EVALUATION
KRIEL COLLIERY

J1-2

———ProRough-31(R)———

IRI (RARS_80) from profile elevations.

Input File : KL-11-LI.L_R

Route description : KRIEL Road 11 (Loaded inner)

File creation date : 1995/12/11

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 1.698

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max IRI	Max l	Max ul
0.1	2.83	3.92	6.86	10	10.00	3.92	10.00
0.2	2.57	3.44	3.41	4.35	4.35	3.44	4.35
0.3	2.05	3	2.48	8.77	8.77	3.00	8.77
0.4	6.02	5.84	2.31	9.08	9.08	6.02	9.08
0.5	8.8	7.98	4	3.97	8.80	8.80	4.00
0.6	4.22	10.38			10.38	10.38	ERR
0.7	4.82	8.47	4.4	7.55	8.47	8.47	7.55
0.8			4.9	7.78	7.78	ERR	7.78
0.9	4.49	6.39			6.39	6.39	ERR
1	7.63	8.35	7.77	8.44	8.44	8.35	8.44
1.1			4.92	9.18	9.18	ERR	9.18
1.2		6.84			6.84	6.84	ERR
1.3	3.76	3.7		6.53	6.53	3.76	6.53
1.4	8.87	8.18	11.12	6.67	11.12	8.87	11.12
1.5		9.57	4.25	6.3	9.57	9.57	6.30
1.6		11.73	7.31	8.3	11.73	11.73	8.30

J1-3

——ProRough-31(R)——

IRI (RARS_80) from profile elevations

Input File : **KL-6-LI.L_R**

Route description : **KRIEL Road 6 (Loaded inner)**

File creation date : **1995/12/11**

Profile interval (mm) : **246.55**

Wheeltrack : **INNER**

Start at km : **1.849**

Measuring direction : **NEGATIVE (-)**

Correlation equation : **IRI(final)=1.018*IRI(calc)+0.234**

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max IRI	Max l	Max ul
0.1	5.91	3.95	8.99		8.99	5.91	8.99
0.2	5.28	8.57	7.65	5.6	8.57	8.57	7.65
0.3	7.24	6.45	11.21	4.97	11.21	7.24	11.21
0.4	4.81	9.75	9.98	8.07	9.98	9.75	9.98
0.5	3.89	3.77	4.02	4.48	4.48	3.89	4.48
0.6	4.64	5.62	3.93	4.9	5.62	5.62	4.90
0.7	6.79	9.47	5.43	7.38	9.47	9.47	7.38
0.8	9		6.48		9.00	9.00	6.48
0.9	5.38	6.64			6.64	6.64	ERR
1	2.98	5.72		6.85	6.85	5.72	6.85
1.1	3.08	6.33	6.07	4.33	6.33	6.33	6.07
1.2	3.44	10.1	3.28	7.61	10.10	10.10	7.61
1.3	4.69	9.43	3.61	5.78	9.43	9.43	5.78
1.4	7.4		4.77	4.61	7.40	7.40	4.77
1.5	7.75			7.05	7.75	7.75	7.05
1.6	6.64	8.62	6.52		8.62	8.62	6.52
1.7	3.62	9.2	5.04	9.05	9.20	9.20	9.05
1.8		10.62	3.92	6.41	10.62	10.62	6.41

J1-4

———ProRough-31(R)———

IRI (RARS_80) from profile elevations

Input File : KL-MH-UO.L_R

Route description : KRIEL Road 7 (Loaded inner)

File creation date : 1995/12/11

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 1.600

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max IRI	Max I	Max ul
0.1	2.9	2.88			2.90	2.90	ERR
0.2	4.72	3.31	2.79	2.78	4.72	4.72	2.79
0.3	4.16	3.7	3.49	4.27	4.27	4.16	4.27
0.4	3.33		5.76		5.76	3.33	5.76
0.5	2.68	3.88	5.11	4.49	5.11	3.88	5.11
0.6	3.5	4.2	2.79	3.72	4.20	4.20	3.72
0.7	2.67	9.75	3.3	4.88	9.75	9.75	4.88
0.8	3.34	4.9	6.5	11.05	11.05	4.90	11.05
0.9	3.26		3.86		3.86	3.26	3.86
1	4.68	12.55		8.03	12.55	12.55	8.03
1.1	2.83				2.83	2.83	ERR
1.2	5.18				5.18	5.18	ERR
1.3	5.8				5.80	5.80	ERR
1.4	6.5	5.2	5.83	7.6	7.60	6.50	7.60
1.5	7.63	5.4	6.35	11.21	11.21	7.63	11.21

———ProRough-31(R)———

IRI (RARS_80) from profile elevations

Input File : KL-MH-LI.L_R

Route description : KRIEL - Main Haul (Loaded Inner)

File creation date : 1995/12/11

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 4.592

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max IRI	Max l	Max ul
0.1	6.24	5.41	5.25	7.78	7.78	6.24	7.78
0.2	5.07	4	5.42	5.02	5.42	5.07	5.42
0.3	3.26	4.93	4.39	4.07	4.93	4.93	4.39
0.4		6.62	6.08	4.56	6.62	6.62	6.08
0.5	4.38	4.36	5.08	2.59	5.08	4.38	5.08
0.6	5.94	3.54		4.89	5.94	5.94	4.89
0.7	4.77	3.69	5.57	3.23	5.57	4.77	5.57
0.8	6.34	6.73	4.78	3.67	6.73	6.73	4.78
0.9	4.17	3.63	4.1	3.19	4.17	4.17	4.10
1	3.59	3.18	4.73	3.6	4.73	3.59	4.73
1.1	4.58	4.19	4.23	3.69	4.58	4.58	4.23
1.2	3.87	5.07	2.67	2.2	5.07	5.07	2.67
1.3	4.93	4.53	2.34	2.58	4.93	4.93	2.58
1.4	5	3.44	6.58	2.6	6.58	5.00	6.58
1.5	5.29	4.47	4.07	2.05	5.29	5.29	4.07
1.6	4.45	4.32	2.91	2.36	4.45	4.45	2.91
1.7	4.95	4.46	2.3	2.65	4.95	4.95	2.65
1.8	10.92	5.63	2.65	2.59	10.92	10.92	2.65
1.9		6.65	3.03	2.3	6.65	6.65	3.03
2	6.86	5.97	5.5	2.11	6.86	6.86	5.50
2.1	6.18	6.41	5.12	2.63	6.41	6.41	5.12
2.2	5.15	4.62	2.96	3.1	5.15	5.15	3.10
2.3	4.32	5.3	3.27	2.9	5.30	5.30	3.27

J1-6

2.4	3.32	4.22	4.51	2.84	4.51	4.22	4.51
2.5	3.86	3.85	3.4	3.2	3.86	3.86	3.40
2.6	4.01	4.75	4.32	3.12	4.75	4.75	4.32
2.7		6.12	6.26	3.65	6.26	6.12	6.26
2.8	7.07	4.74	6.62	3.96	7.07	7.07	6.62
2.9	4.26	3.73	3.83	2.62	4.26	4.26	3.83
3	4.19	5.62	3.65	3.4	5.62	5.62	3.65
3.1	3.45	3.35	3.71	4.16	4.16	3.45	4.16
3.2	3.62	5.91	3	3.16	5.91	5.91	3.16
3.3	9.11	9.97	3.37	3.75	9.97	9.97	3.75
3.4	5.4	10.36	5.23	3.43	10.36	10.36	5.23
3.5	4.49	10.01	4.73	2.86	10.01	10.01	4.73
3.6	4.03	7.31	4.53	5.98	7.31	7.31	5.98
3.7	6.12	10.14	4.78	4.06	10.14	10.14	4.78
3.8	5.32	6.15	5.53	3.53	6.15	6.15	5.53
3.9	5.09	5.17	3.26	3.66	5.17	5.17	3.66
4	4.8	6.56	4.34	2.87	6.56	6.56	4.34
4.1	6.65		5.72	3.02	6.65	6.65	5.72
4.2	8.17	4.69	2.83	2.9	8.17	8.17	2.90
4.3	6.43	6.12	2.7	2.42	6.43	6.43	2.70
4.4			4.33	3.88	4.33	ERR	4.33
4.5	5.3	7.66			7.66	7.66	ERR

APPENDIX J2

RESULTS OF HAUL ROAD IRI ROUGHNESS EVALUATION KROMDRAAI COLLIERY

J2-2

———ProRough-31(R)———

IRI (RARS_80) from profile elevations

Input File : KD-H2-LI.L_R

Route description : KROMDRAAI Haul 2 (Loaded inner)

File creation date : 1995/12/08

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 0.000

Measuring direction : POSITIVE (+)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max iri	maxl	max ul
0.1	3.65	4.66	6.27	5.25	6.27	4.66	6.27
0.2	3.13	5.41	7.81	7.8	7.81	5.41	7.81
0.3	4.31	7.58	5.99	3.18	7.58	7.58	5.99
0.4	3.61	5.65	7.34	4.09	7.34	5.65	7.34
0.5	4.15	4.44	6.78	6.74	6.78	4.44	6.78
0.6	5.09	5.05	4.28	4.74	5.09	5.09	4.74
0.7	8.7	3.67	2.98	4.31	8.70	8.70	4.31
0.8	4.11	3.84	4.66	5.26	5.26	4.11	5.26
0.9	7.76	3.75	2.95	3.77	7.76	7.76	3.77
1	3.91	3.92	4.56	8.29	8.29	3.92	8.29
1.1	3.49	3.37	6.85	5.58	6.85	3.49	6.85
1.2	5.41	3.12	5.25	7.07	7.07	5.41	7.07
1.3	3.44	2.9	5.24	7.07	7.07	3.44	7.07
1.4	5.19	3.35	4.12	3.57	5.19	5.19	4.12
1.5	7.17	2.79	3.19	3.84	7.17	7.17	3.84
1.6	3.21	2.77	3.7	2.22	3.70	3.21	3.70
1.7	5.21	3.74	3.08	2.8	5.21	5.21	3.08
1.8	4.71	4.63	3.29	2.46	4.71	4.71	3.29
1.9	3.75	2.96	3.25	3.16	3.75	3.75	3.25
2	3.96	2.98	3.04	3.59	3.96	3.96	3.59
2.1	4.5	4.12	3.77	2.23	4.50	4.50	3.77
2.2	4.63	4.01	3.94	3.05	4.63	4.63	3.94
2.3	4.29	3.88	7.95	5.01	7.95	4.29	7.95
2.4	3.67	4.8	5.04	4.23	5.04	4.80	5.04

———ProRough-31(R)———

IRI (RARS_80) from profile elevations

Input File : KD-H1-LI.L_R

Route description : KROMDRAAI - Haul 1 (Loaded inner)

File creation date : 1995/12/08

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 1.534

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	max iri	maxl	max ul
0.1	3.18	3.57	4.07	3.57	4.07	3.57	4.07
0.2	2.43	2.43	3.64	3.93	3.93	2.43	3.93
0.3	3.21	2.94	4.03	3.93	4.03	3.21	4.03
0.4	2.89	2.6	4.15	4.75	4.75	2.89	4.75
0.5	2.95	3.38	3.07	4.81	4.81	3.38	4.81
0.6	3.31	2.99	3.03	5.18	5.18	3.31	5.18
0.7	2.76	2.77	2.96	3.22	3.22	2.77	3.22
0.8	3.34	3.04	2.69	2.42	3.34	3.34	2.69
0.9	4.5	4.29	3.62	3.47	4.50	4.50	3.62
1	4.06	4.67	3.97	4.26	4.67	4.67	4.26
1.1	5.21	4.23	4.06	3.62	5.21	5.21	4.06
1.2	5.23	4.19	4.83	3.68	5.23	5.23	4.83
1.3	4.58	3.39	3.14	4.15	4.58	4.58	4.15
1.4	5.69	6.61	4.58	4.32	6.61	6.61	4.58
1.5	6.82	5.97	4.08	4.65	6.82	6.82	4.65

J2-4

———ProRough-31(R)———

IRI (RARS_80) from profile elevations

Input File : KD-MH-LI.L_R

Route description : KROMDRAAI - Main haul (Loaded inner)

File creation date : 1995/12/08

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 0.900

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max iri	maxl	max ul
0.1	5.64	5.09	7.04	8.06	8.06	5.64	8.06
0.2	4.47	6.62	3.86	5.76	6.62	6.62	5.76
0.3	4.26	7.24	4.61	8.27	8.27	7.24	8.27
0.4	3.56	7.09	3.77	3.86	7.09	7.09	3.86
0.5	4.63	3.94	2.95	3.29	4.63	4.63	3.29
0.6	5.16	4.8	4.1	3.77	5.16	5.16	4.10
0.7	4.12	6.07	3.97	3.83	6.07	6.07	3.97
0.8	4.6	4.67	2.42	2.75	4.67	4.67	2.75

APPENDIX J3

RESULTS OF HAUL ROAD IRI ROUGHNESS EVALUATION NEW VAAL COLLIERY

J3-2

———ProRough-31(R)———

IRI (RARS_80) from profile elevations

Input File : NV-MH-LI.L_R

Route description : NEW VAAL - Main Haul (Loaded inner)

File creation date : 1995/12/08

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 5.238

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max IRI	max l	max r
0.1	4.04	3.8	3.66	6.67	6.67	4.04	6.67
0.2	5.91	7.12	2.78	6.09	7.12	7.12	6.09
0.3	3.24	4.76	2.63	4.21	4.76	4.76	4.21
0.4	2.77	3.53	1.89	5.07	5.07	3.53	5.07
0.5	4.33	4.27	3.5	3.58	4.33	4.33	3.58
0.6	4.67	4.49	2.75	4.37	4.67	4.67	4.37
0.7	3.63	4.23	3.23	4.35	4.35	4.23	4.35
0.8	4.01	4.18	3.06	4.28	4.28	4.18	4.28
0.9	3.1	3.45	2.67	4.37	4.37	3.45	4.37
1	3.08	3.54	3.53	4.84	4.84	3.54	4.84
1.1	3.79	4.12	3.15	4.34	4.34	4.12	4.34
1.2	3.23	3.71	3.43	4.06	4.06	3.71	4.06
1.3	3.5	3.92	4.02	4.39	4.39	3.92	4.39
1.4	3.81	4.12	3.55	3	4.12	4.12	3.55
1.5	3.11	4.82	5.04	3	5.04	4.82	5.04
1.6	3.86	3.38	4.58	3.27	4.58	3.86	4.58
1.7	6.68	7	4.04	4.08	7.00	7.00	4.08
1.8	3.86	4.18	4.84	5.08	5.08	4.18	5.08
1.9	2.11	3.25	3.96	4.17	4.17	3.25	4.17
2	5.09	2.97	3.03	4.2	5.09	5.09	4.20
2.1	5.17	5.9	2.66	4.47	5.90	5.90	4.47
2.2	3.49	3.51	4.64	4.02	4.64	3.51	4.64
2.3	2.77	2.9	4.39	8.27	8.27	2.90	8.27
2.4	2.29	3.09	2.91	3.34	3.34	3.09	3.34

J3-3

2.5	2.74	3.21	2.79	2.83	3.21	3.21	2.83
2.6	2.91	3.27	3.01	2.79	3.27	3.27	3.01
2.7	3.09	4.97	4.15	3.42	4.97	4.97	4.15
2.8	3.31	3.64	2.73	3.49	3.64	3.64	3.49
2.9	3.82	5.4	3.49	3.23	5.40	5.40	3.49
3	3.58	6.05	3.4	3.84	6.05	6.05	3.84
3.1	4.47	5.32	3.74	3.84	5.32	5.32	3.84
3.2	4.04	4.04	5.07	3.28	5.07	4.04	5.07
3.3	3	3.41	4.2	2.93	4.20	3.41	4.20
3.4	3.35	3.33	4.14	2.69	4.14	3.35	4.14
3.5	3.5	3.21	3.67	3.77	3.77	3.50	3.77
3.6	4.35	3.03	3.3	3.61	4.35	4.35	3.61
3.7	4.47	3.42	3.89	3.76	4.47	4.47	3.89
3.8	3.54	3.95	3.5	3.56	3.95	3.95	3.56
3.9	3.1	3.15	4.25	7.04	7.04	3.15	7.04
4	3.43	2.85	3.56	4.72	4.72	3.43	4.72
4.1	2.53	3.81	2.07	3.01	3.81	3.81	3.01
4.2	2.76	3	2.92	5.35	5.35	3.00	5.35
4.3	3.63	3.47	4.62	6.53	6.53	3.63	6.53
4.4	3	3.92	4.22	7.97	7.97	3.92	7.97
4.5	2.73	3.57	2.35	5.36	5.36	3.57	5.36
4.6	3.19	3.82	1.96	5.43	5.43	3.82	5.43

———ProRough-31(R)———

IRI (RARS_80) from profile elevations

Input File : NV-R3-LI.L_R

Route description : NEW VAAL - Road 3 (Loaded inner)

File creation date : 1995/12/08

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 0.697

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max iri	Max l	Max ul
0.1	4.89	5.65	5.91	5.91	4.89	5.91	5.91
0.2	5.36	5.42	2.3	5.42	5.36	5.42	3.86
0.3	4.83	7.09	3.93	7.09	4.83	7.09	5.51
0.4	5.33	4.67	6.05	6.05	5.33	6.05	6.05
0.5	10.53	13.07	5.96	13.07	10.53	13.07	9.52
0.6	10.01	11.84	7.76	11.84	10.01	11.84	9.80

J3-5

———ProRough-31(R)———

IRI (RARS_80) from profile elevations

Input File : NV-R5-LI.L_R

Route description : NEW VAAL - Road 5 (Loaded inner)

File creation date : 1995/12/08

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 0.746

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max IRI	max l	max r
0.1	3.11	4.07	3.95	4.68	4.68	4.07	4.68
0.2	3.67	4.46	3.23	2.84	4.46	4.46	3.23
0.3	3.45	3.16	3.25	2.86	3.45	3.45	3.25
0.4	3.58	3.09	3.25	3.75	3.75	3.58	3.75
0.5	3.99	3.92	3.72	3.32	3.99	3.99	3.72
0.6	4.24	6.37	3.25	5.18	6.37	6.37	5.18
0.7	2.7	3.38	4.47	3.77	4.47	3.38	4.47

APPENDIX J4

RESULTS OF HAUL ROAD IRI ROUGHNESS EVALUATION
KLEINKOPJE COLLIERY

J4-2

——ProRough-31(R)——

IRI (RARS_80) from profile elevations

Input File : KK-2A-LI.L_R

Route description : KLEINKOPPIE Road 2A (Loaded inner)

File creation date : 1995/12/11

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 2.900

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max IRI	max l	max ul
0.1		6.76			6.76	6.76	ERR
0.2	5.99	5.24		11.02	11.02	5.99	11.02
0.3	4.93	4.08	3.76	5.54	5.54	4.93	5.54
0.4	4.33	4.77	5.4	4.84	5.40	4.77	5.40
0.5	5.64	3.3	5.04	4.18	5.64	5.64	5.04
0.6	3.24	4.03	5.41	4.26	5.41	4.03	5.41
0.7	3.78	3.93	4.93	5.16	5.16	3.93	5.16
0.8	5.11	4.69	3.91	5.57	5.57	5.11	5.57
0.9	3.11	3.28		8.06	8.06	3.28	8.06
1	3.56	2.7	4.92	4.3	4.92	3.56	4.92
1.1	3.85	3.24	4.98	2.82	4.98	3.85	4.98
1.2	3.77	4.62	6.8	3.94	6.80	4.62	6.80
1.3	3.61	3.59	5.36	3.01	5.36	3.61	5.36
1.4	2.63	2.62	3.48	4.12	4.12	2.63	4.12
1.5	3.45	3.61	2.7	3.11	3.61	3.61	3.11
1.6	4.66	4.6	2.18	2.95	4.66	4.66	2.95
1.7	4.18	3.65	3.88	4.08	4.18	4.18	4.08
1.8	3.52	2.94	5.09	5.68	5.68	3.52	5.68
1.9	2.91	5.35	3.02	3.28	5.35	5.35	3.28
2	2.25	4.51	3.25	3.11	4.51	4.51	3.25
2.1	3.26	3.82	3.39	2.7	3.82	3.82	3.39
2.2	2.46	3.07	2.81	2.52	3.07	3.07	2.81
2.3	3.7	4.13	2.55	2.59	4.13	4.13	2.59

J4-3

2.4	3.45	3.46	3.77	2.96	3.77	3.46	3.77
2.5	5.35	5.18	3.18	2.23	5.35	5.35	3.18
2.6	4.5	4.58		5.79	5.79	4.58	5.79
2.7	3.41	4.2	4.76	4.69	4.76	4.20	4.76
2.8	6.27	5.19	4.11	4.03	6.27	6.27	4.11

——————ProRough-31(R)——————

Input File : KK-3A-LI.L_R

Route description : KLEINKOPPIE Road 3A (Loaded inner)

File creation date : 1995/12/11

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 2.600

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max IRI	max l	max ul
0.1	4.28	5.04	4.51	4.15	5.04	5.04	4.51
0.2	4.27	3.78	3.29	3.44	4.27	4.27	3.44
0.3	3.44	4.59	3.92	4.89	4.89	4.59	4.89
0.4	4.03	4.77	3.31	4.59	4.77	4.77	4.59
0.5	3.69	4.77	4.1	3.85	4.77	4.77	4.10
0.6	7.2	3.46		6.74	7.20	7.20	6.74
0.7	6.33	5.41	5.75	4.03	6.33	6.33	5.75
0.8	6.09	3.77	4.72	3.94	6.09	6.09	4.72
0.9	3.04	3.92	6.05	3.87	6.05	3.92	6.05
1	4.93	3.5	4.16	2.87	4.93	4.93	4.16
1.1	5.73	5.37	4.18	3.02	5.73	5.73	4.18
1.2	6.5	5.09	5.63	6.45	6.50	6.50	6.45
1.3		8.82	5.52	4.81	8.82	8.82	5.52
1.4	6.02	5.59			6.02	6.02	ERR
1.5	5.95	5.34	4.38	5.52	5.95	5.95	5.52
1.6	6.8	10.3	3.96	5.44	10.30	10.30	5.44
1.7		4.62	5.95	4.58	5.95	4.62	5.95
1.8	4.39	6.58	4.62	6.02	6.58	6.58	6.02
1.9	5.22	7.84	7.27	6.36	7.84	7.84	7.27
2	6.26	8.48	6.23	7.37	8.48	8.48	7.37
2.1	4.8	5.97	6.69	7.29	7.29	5.97	7.29
2.2		6.64	5.25	7.24	7.24	6.64	7.24
2.3	4.19	4.25	5.39	6.92	6.92	4.25	6.92
2.4	5.44	9	5.72		9.00	9.00	5.72
2.5	3.84	4.81	6.22	8.37	8.37	4.81	8.37

J4-5

———ProRough-31(R)———

IRI (RARS_80) from profile elevations

Input File : KK-5W-LI.L_R

Route description : KLEINKOPPIE Road 5W (Loaded inner)

File creation date : 1995/12/11

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 2.842

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max IRI	max l	max ul
0.1	5.01	5.92	4.74	3.6	5.92	5.92	4.74
0.2	5.07	6.66	4.99	6.34	6.66	6.66	6.34
0.3	3.98	4.72	5.45	4.94	5.45	4.72	5.45
0.4	2.73	2.92	4.48	4.38	4.48	2.92	4.48
0.5	2.99	4.31	3.24	3.16	4.31	4.31	3.24
0.6	2.42	2.28	2.68	4.29	4.29	2.42	4.29
0.7	3.12	2.22	2.42	3.75	3.75	3.12	3.75
0.8	3.03	3.12	3.5	3.92	3.92	3.12	3.92
0.9	3.24	2.78	3.07	4.02	4.02	3.24	4.02
1	2.79	3.08	2.83	3.54	3.54	3.08	3.54
1.1	5.24	3.77	2.33	3.06	5.24	5.24	3.06
1.2	3.54	4.09	3.72	3.82	4.09	4.09	3.82
1.3	4.11	4.63	3.06	4.24	4.63	4.63	4.24
1.4	3.45	3.1	3.38	2.69	3.45	3.45	3.38
1.5	3.74	4.18	3.51	2.82	4.18	4.18	3.51
1.6	5.59	5.63	3.08	3.18	5.63	5.63	3.18
1.7	5.72	7.76	3.1	2.57	7.76	7.76	3.10
1.8	3.92	5.36	3.47	2.64	5.36	5.36	3.47
1.9	4.31	6.2	3.67	4.37	6.20	6.20	4.37
2	4.47	5.92	3.42	6.94	6.94	5.92	6.94
2.1	2.78	5.59	5	6.22	6.22	5.59	6.22
2.2	3.01	4.67	3.09	4.11	4.67	4.67	4.11
2.3	4.78	4.35	2.35	4.25	4.78	4.78	4.25

J4-6

2.4	8.1	8.16	4.99	5.7	8.16	8.16	5.70
2.5		9.47	4.89	5.63	9.47	9.47	5.63
2.6	8.11	4.75		4.23	8.11	8.11	4.23
2.7		9.91	8.04	3.68	9.91	9.91	8.04
2.8	5.29	7.08	7.92	8.5	8.50	7.08	8.50

J4-7

—————ProRough-31(R)—————

IRI (RARS_80) from profile elevations

Input File : KK-14-LI.L_R

Route description : KLEINKOPPIE Road 14 (Loaded inner)

File creation date : 1995/12/11

Profile interval (mm) : 246.55

Wheeltrack : INNER

Start at km : 2.420

Measuring direction : NEGATIVE (-)

Correlation equation : IRI(final)=1.018*IRI(calc)+0.234

km	IRI (100m intervals)						
	LADEN I	LADEN O	UNLADEN I	UNLADEN O	Max IRI	max l	max ul
0.1	4.21	7.08	5.54	4.98	7.08	7.08	5.54
0.2		6.67	5.12	5.8	6.67	6.67	5.80
0.3	4.03	8.21	4.41	6.28	8.21	8.21	6.28
0.4	4.45	10.83	4.61	8.06	10.83	10.83	8.06
0.5	3.74	10.08	4.9	5.5	10.08	10.08	5.50
0.6	4.72	8.33	4.01	6.55	8.33	8.33	6.55
0.7	5.25	8.41	5.28	9.55	9.55	8.41	9.55
0.8	4.47	9.04	5.01	5.06	9.04	9.04	5.06
0.9	4.23	6.01			6.01	6.01	ERR
1		6.36	5.81	4.69	6.36	6.36	5.81
1.1	3.77	5.42	5.62	4.49	5.62	5.42	5.62
1.2	3.46	6.45	3.7	3.91	6.45	6.45	3.91
1.3	4.21	5.24	3.43	5.78	5.78	5.24	5.78
1.4	3.13	5.32	7.08	5.68	7.08	5.32	7.08
1.5	5.6	4.88	4.2	4.82	5.60	5.60	4.82
1.6	4.58	6.8	3.31	4.72	6.80	6.80	4.72
1.7	5.91	6.61			6.61	6.61	ERR
1.8	7.33	7.16	3.72	4.64	7.33	7.33	4.64
1.9	7.27			9.18	9.18	7.27	9.18
2	5.58	8.91	8.75	7.26	8.91	8.91	8.75
2.1	4.41	7.57		7.63	7.63	7.57	7.63
2.2	6.19	7.85	5.24	4.72	7.85	7.85	5.24
2.3	6.62	8.34	3.46	4.54	8.34	8.34	4.54
2.4	13.64	15.41	4.03	5.03	15.41	15.41	5.03

APPENDIX K1

RESULTS OF HAUL ROAD SUBJECTIVE ROUGHNESS EVALUATIONS
KRIEL COLLIERY

K1-2

SUMMARY OF RESULTS, MAXIMUM SECTION AVERAGE IRI (m/km) ROUGHNESS SCORE WITH SUBJECTIVE EVALUATION OF ROUGHNESS

Kriel Colliery

km	Main HR	IRI(x4)	Ramp 6	IRI(x4)	Ramp 7	IRI(x4)	Ramp 8/11	IRI(x4)
0.1	26	31.12	27	35.96	31	11.60	33	40.00
0.2	26	21.68	22	34.28	18	18.88	20	17.40
0.3	24	19.72	41	44.84	22	17.08	20	35.08
0.4	32	26.48	44	39.92	29	23.04	24	36.32
0.5	30	20.32	28	17.92	21	20.44	43	35.20
0.6	24	23.76	32	22.48	35	16.80	43	41.52
0.7	28	22.28	37	37.88	46	39.00	40	33.88
0.8	38	26.92	40	36.00	49	44.20	37	31.12
0.9	24	16.68	33	26.56	46	15.44	44	25.56
1.0	20	18.92	24	27.40	60	50.20	43	33.76
1.1	20	18.32	33	25.32	41	11.32	47	36.72
1.2	20	20.28	30	40.40	63	20.72	54	27.36
1.3	28	19.72	43	37.72	67	23.20	43	26.12
1.4	31	26.32	34	29.60	75	30.40	49	44.48
1.5	24	21.16	22	31.00			43	38.28
1.6	18	17.80	42	34.48				
1.7	24	19.80		36.80				
1.8	25	43.68						
1.9	50	26.60						
2.0	34	27.44						
2.1	26	25.64						
2.2	28	20.60						
2.3	24	21.20						
2.4	30	18.04						
2.5	24	15.44						
2.6	26	19.00						
2.7	24	25.04						
2.8	29	28.28						
2.9	34	17.04						
3.0	22	22.48						
3.1	28	16.64						
3.2	25	23.64						

K1-3

SUMMARY OF RESULTS, MAXIMUM SECTION AVERAGE IRI (m/km) ROUGHNESS SCORE WITH SUBJECTIVE EVALUATION OF ROUGHNESS
Kriel Colliery

km	Main HR	IRI(x4)	Ramp 6	IRI(x4)	Ramp 7	IRI(x4)	Ramp 8/11	IRI(x4)
3.3	39	39.88						
3.4	41	41.44						
3.5	52	40.04						
3.6	45	29.24						
3.7	50	40.56						
3.8	35	24.60						
3.9	29	20.68						
4.0	30	26.24						
4.1	24	26.60						
4.2	29	32.68						
4.3	29	25.72						
4.4	34	17.32						
4.5	32	30.64						

K1-4

Kriel Mine		
Main HR Segment	**100**	
	Degree	**Extent**
Potholes	2	4
Corrugations	2	1
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**26**

Kriel Mine		
Main HR Segment	**200**	
	Degree	**Extent**
Potholes	2	4
Corrugations	2	2
Rutting	2	1
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**26**

Kriel Mine		
Main HR Segment	**300**	
	Degree	**Extent**
Potholes	2	4
Corrugations	2	1
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**24**

Kriel Mine		
Main HR Segment	**400**	
	Degree	**Extent**
Potholes	3	4
Corrugations	2	3
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**32**

K1-5

Kriel Mine		
Main HR Segment	**500**	
	Degree	**Extent**
Potholes	3	4
Corrugations	2	3
Rutting	2	1
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**30**

Kriel Mine		
Main HR Segment	**600**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**24**

Kriel Mine		
Main HR Segment	**700**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	3
Rutting	2	2
Loose Material	3	2
Stoniness - fixed	2	3
Sum Degree x Extent		**28**

Kriel Mine		
Main HR Segment	**800**	
	Degree	**Extent**
Potholes	2	2
Corrugations	3	3
Rutting	2	2
Loose Material	3	4
Stoniness - fixed	3	3
Sum Degree x Extent		**38**

K1-6

Kriel Mine		
Main HR Segment	**900**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	3	2
Sum Degree x Extent		**24**

Kriel Mine		
Main HR Segment	**1000**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	1
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**20**

Kriel Mine		
Main HR Segment	**1100**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	1
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**20**

Kriel Mine		
Main HR Segment	**1200**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**20**

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K1-7

Kriel Mine		
Main HR Segment	1300	
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		28

Kriel Mine		
Main HR Segment	1400	
	Degree	Extent
Potholes	3	3
Corrugations	3	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		31

Kriel Mine		
Main HR Segment	1500	
	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		24

Kriel Mine		
Main HR Segment	1600	
	Degree	Extent
Potholes	2	2
Corrugations	1	2
Rutting	1	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		18

K1-8

Kriel Mine		
Main HR Segment	**1700**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	3
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**24**

Kriel Mine		
Main HR Segment	**1800**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	1	2
Sum Degree x Extent		**25**

Kriel Mine		
Main HR Segment	**1900**	
	Degree	**Extent**
Potholes	3	3
Corrugations	3	3
Rutting	2	2
Loose Material	3	4
Stoniness - fixed	4	4
Sum Degree x Extent		**50**

Kriel Mine		
Main HR Segment	**2000**	
	Degree	**Extent**
Potholes	2	3
Corrugations	3	3
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	3	3
Sum Degree x Extent		**34**

K1-9

Kriel Mine		
Main HR Segment	2100	
	Degree	Extent
Potholes	2	3
Corrugations	2	3
Rutting	2	2
Loose Material	3	2
Stoniness - fixed	2	2
Sum Degree x Extent		26

Kriel Mine		
Main HR Segment	2200	
	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	4
Sum Degree x Extent		28

Kriel Mine		
Main HR Segment	2300	
	Degree	Extent
Potholes	2	1
Corrugations	2	2
Rutting	2	3
Loose Material	2	4
Stoniness - fixed	2	2
Sum Degree x Extent		24

Kriel Mine		
Main HR Segment	2400	
	Degree	Extent
Potholes	2	2
Corrugations	3	4
Rutting	2	1
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		30

K1-10

Kriel Mine		
Main HR Segment	**2500**	
	Degree	**Extent**
Potholes	2	2
Corrugations	3	2
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**24**

Kriel Mine		
Main HR Segment	**2600**	
	Degree	**Extent**
Potholes	3	2
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**26**

Kriel Mine		
Main HR Segment	**2700**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	3
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**24**

Kriel Mine		
Main HR Segment	**2800**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**29**

K1-11

Kriel Mine		
Main HR Segment	2900	
	Degree	Extent
Potholes	2	3
Corrugations	3	3
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	3	3
Sum Degree x Extent		34

Kriel Mine		
Main HR Segment	3000	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	1
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		22

Kriel Mine		
Main HR Segment	3100	
	Degree	Extent
Potholes	2	1
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	3	4
Sum Degree x Extent		28

Kriel Mine		
Main HR Segment	3200	
	Degree	Extent
Potholes	2	1
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	3	3
Sum Degree x Extent		25

K1-12

Kriel Mine		
Main HR Segment	3300	
	Degree	Extent
Potholes	3	3
Corrugations	3	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	4	4
Sum Degree x Extent		39

Kriel Mine		
Main HR Segment	3400	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	4	4
Sum Degree x Extent		41

Kriel Mine		
Main HR Segment	3500	
	Degree	Extent
Potholes	3	4
Corrugations	2	2
Rutting	3	4
Loose Material	2	2
Stoniness - fixed	4	5
Sum Degree x Extent		52

Kriel Mine		
Main HR Segment	3600	
	Degree	Extent
Potholes	4	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	4	4
Sum Degree x Extent		45

K1-13

Kriel Mine		
Main HR Segment	**3700**	
	Degree	**Extent**
Potholes	4	3
Corrugations	2	2
Rutting	3	4
Loose Material	2	3
Stoniness - fixed	4	4
Sum Degree x Extent		**50**

Kriel Mine		
Main HR Segment	**3800**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	4	3
Sum Degree x Extent		**35**

Kriel Mine		
Main HR Segment	**3900**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	3	3
Sum Degree x Extent		**29**

Kriel Mine		
Main HR Segment	**4000**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	3	4
Sum Degree x Extent		**30**

K1-14

Kriel Mine		
Main HR Segment	**4100**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**24**

Kriel Mine		
Main HR Segment	**4200**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**29**

Kriel Mine		
Main HR Segment	**4300**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**29**

Kriel Mine		
Main HR Segment	**4400**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	3
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**34**

K1-15

Kriel Mine		
Main HR Segment	4500	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		32

Kriel Mine	Main HR
Segment	Comment
400	Junction workshop
500	Junction workshop
3500	Pothole at edge of road
4300	Approach to underpass
4366	Underpass
4500	End main HR

K1-16

Kriel Mine		
Ramp 6 Segment	**100**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**27**

Kriel Mine		
Ramp 6 Segment	**200**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**22**

Kriel Mine		
Ramp 6 Segment	**300**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	4
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	3	4
Sum Degree x Extent		**41**

Kriel Mine		
Ramp 6 Segment	**400**	
	Degree	**Extent**
Potholes	4	4
Corrugations	2	4
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	4
Sum Degree x Extent		**44**

K1-17

Kriel Mine		
Ramp 6 Segment	**500**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	4
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**28**

Kriel Mine		
Ramp 6 Segment	**600**	
	Degree	**Extent**
Potholes	4	2
Corrugations	2	4
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**32**

Kriel Mine		
Ramp 6 Segment	**700**	
	Degree	**Extent**
Potholes	3	3
Corrugations	3	2
Rutting	4	3
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**37**

Kriel Mine		
Ramp 6 Segment	**800**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	2
Rutting	3	3
Loose Material	3	4
Stoniness - fixed	3	2
Sum Degree x Extent		**40**

K1-18

Kriel Mine		
Ramp 6 Segment	900	
	Degree	Extent
Potholes	3	3
Corrugations	2	3
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	2	3
Sum Degree x Extent		33

Kriel Mine		
Ramp 6 Segment	1000	
	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		24

Kriel Mine		
Ramp 6 Segment	1100	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	1	2
Loose Material	2	3
Stoniness - fixed	4	3
Sum Degree x Extent		33

Kriel Mine		
Ramp 6 Segment	1200	
	Degree	Extent
Potholes	2	3
Corrugations	3	2
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	3	4
Sum Degree x Extent		30

K1-19

Kriel Mine		
Ramp 6 Segment	**1300**	
	Degree	**Extent**
Potholes	3	3
Corrugations	3	3
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	3	4
Sum Degree x Extent		**43**

Kriel Mine		
Ramp 6 Segment	**1400**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	3	4
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**34**

Kriel Mine		
Ramp 6 Segment	**1500**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**22**

Kriel Mine		
Ramp 6 Segment	**1600**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	3
Rutting	3	3
Loose Material	3	3
Stoniness - fixed	3	3
Sum Degree x Extent		**42**

K1-20

Kriel Mine	**Ramp 6**
Segment	**Comment**
100	Junction
300	Junction
700	Wet and cut up
1600	End ramp 6

K1-21

Kriel Mine		
Ramp 7 Segment	**100**	
	Degree	**Extent**
Potholes	4	2
Corrugations	2	2
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**31**

Kriel Mine		
Ramp 7 Segment	**200**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	1
Rutting	2	1
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**18**

Kriel Mine		
Ramp 7 Segment	**300**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	1
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**22**

Kriel Mine		
Ramp 7 Segment	**400**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**29**

K1-22

Kriel Mine		
Ramp 7 Segment	**500**	
	Degree	**Extent**
Potholes	2	2
Corrugations	1	1
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**21**

Kriel Mine		
Ramp 7 Segment	**600**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	4
Rutting	3	2
Loose Material	2	3
Stoniness - fixed	3	3
Sum Degree x Extent		**35**

Kriel Mine		
Ramp 7 Segment	**700**	
	Degree	**Extent**
Potholes	4	3
Corrugations	3	4
Rutting	2	2
Loose Material	3	3
Stoniness - fixed	3	3
Sum Degree x Extent		**46**

Kriel Mine		
Ramp 7 Segment	**800**	
	Degree	**Extent**
Potholes	3	3
Corrugations	4	4
Rutting	3	4
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**49**

K1-23

Kriel Mine		
Ramp 7 Segment	900	
	Degree	Extent
Potholes	3	3
Corrugations	3	4
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	3	4
Sum Degree x Extent		**46**

Kriel Mine		
Ramp 7 Segment	1000	
	Degree	Extent
Potholes	4	3
Corrugations	2	3
Rutting	3	4
Loose Material	3	5
Stoniness - fixed	3	5
Sum Degree x Extent		**60**

Kriel Mine		
Ramp 7 Segment	1100	
	Degree	Extent
Potholes	3	3
Corrugations	2	1
Rutting	3	4
Loose Material	3	3
Stoniness - fixed	3	3
Sum Degree x Extent		**41**

Kriel Mine		
Ramp 7 Segment	1200	
	Degree	Extent
Potholes	4	4
Corrugations	3	3
Rutting	3	3
Loose Material	3	3
Stoniness - fixed	4	5
Sum Degree x Extent		**63**

K1-24

Kriel Mine		
Ramp 7 Segment	**1300**	
	Degree	**Extent**
Potholes	5	3
Corrugations	3	2
Rutting	4	5
Loose Material	2	3
Stoniness - fixed	4	5
Sum Degree x Extent		**67**

Kriel Mine		
Ramp 7 Segment	**1400**	
	Degree	**Extent**
Potholes	4	4
Corrugations	2	3
Rutting	4	5
Loose Material	2	4
Stoniness - fixed	5	5
Sum Degree x Extent		**75**

Kriel Mine	**Ramp 7**
Segment	**Comment**
100	Junction
1000	Parting added
1100	Wet, parting added

K1-25

Kriel Mine Ramp 8/11 Segment 100	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	4	3
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**33**

Kriel Mine Ramp 8/11 Segment 200	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	1	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**20**

Kriel Mine Ramp 8/11 Segment 300	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	2	1
Loose Material	2	3
Stoniness - fixed	2	1
Sum Degree x Extent		**20**

Kriel Mine Ramp 8/11 Segment 400	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	3	2
Sum Degree x Extent		**24**

K1-26

Kriel Mine		
Ramp 8/11 Segment	**500**	
	Degree	**Extent**
Potholes	3	3
Corrugations	3	3
Rutting	2	2
Loose Material	3	4
Stoniness - fixed	3	3
Sum Degree x Extent		**43**

Kriel Mine		
Ramp 8/11 Segment	**600**	
	Degree	**Extent**
Potholes	3	3
Corrugations	3	3
Rutting	2	2
Loose Material	3	3
Stoniness - fixed	3	4
Sum Degree x Extent		**43**

Kriel Mine		
Ramp 8/11 Segment	**700**	
	Degree	**Extent**
Potholes	3	3
Corrugations	3	3
Rutting	2	2
Loose Material	3	3
Stoniness - fixed	3	3
Sum Degree x Extent		**40**

Kriel Mine		
Ramp 8/11 Segment	**800**	
	Degree	**Extent**
Potholes	2	3
Corrugations	3	3
Rutting	2	2
Loose Material	3	3
Stoniness - fixed	3	3
Sum Degree x Extent		**37**

K1-27

Kriel Mine		
Ramp 8/11 Segment	900	
	Degree	Extent
Potholes	3	2
Corrugations	2	3
Rutting	2	2
Loose Material	3	4
Stoniness - fixed	4	4
Sum Degree x Extent		44

Kriel Mine		
Ramp 8/11 Segment	1000	
	Degree	Extent
Potholes	4	3
Corrugations	2	2
Rutting	3	3
Loose Material	3	3
Stoniness - fixed	3	3
Sum Degree x Extent		43

Kriel Mine		
Ramp 8/11 Segment	1100	
	Degree	Extent
Potholes	3	3
Corrugations	2	4
Rutting	3	4
Loose Material	3	2
Stoniness - fixed	3	4
Sum Degree x Extent		47

Kriel Mine		
Ramp 8/11 Segment	1200	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	3	3
Loose Material	4	4
Stoniness - fixed	4	4
Sum Degree x Extent		54

K1-28

Kriel Mine		
Ramp 8/11 Segment	1300	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	3	2
Loose Material	3	4
Stoniness - fixed	3	4
Sum Degree x Extent		43

Kriel Mine		
Ramp 8/11 Segment	1400	
	Degree	Extent
Potholes	3	4
Corrugations	3	2
Rutting	2	4
Loose Material	2	4
Stoniness - fixed	3	5
Sum Degree x Extent		49

Kriel Mine		
Ramp 8/11 Segment	1500	
	Degree	Extent
Potholes	2	3
Corrugations	3	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	4	4
Sum Degree x Extent		43

Kriel Mine	Ramp 8/11
Segment	Comment
100	Junction
500	Junction (ramp 8)
700	Uphill on spoils road
1100	Gulley erosion

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APPENDIX K2

RESULTS OF HAUL ROAD SUBJECTIVE ROUGHNESS EVALUATIONS KROMDRAAI COLLIERY

K2-2

SUMMARY OF RESULTS, MAXIMUM AVERAGE IRI (m/km) ROUGHNESS SCORE WITH SUBJECTIVE EVALUATION OF ROUGHNESS

Kromdraai Colliery

km	Main HR	IRI(x4)	HR1	IRI(x4)	HR2	IRI(x4)
0.1	29	32.24	14	16.28	11	25.08
0.2	24	26.48	16	15.72	26	31.24
0.3	25	33.08	18	16.12	20	30.32
0.4	22	28.36	17	19	22	29.36
0.5	24	18.52	22	19.24	16	27.12
0.6	23	20.64	20	20.72	26	20.36
0.7	21	24.28	14	12.88	26	34.8
0.8	23	18.68	18	13.36	15	21.04
0.9	22		16	18	21	31.04
1.0			19	18.68	29	33.16
1.1			18	20.84	31	27.4
1.2			18	20.92	30	28.28
1.3			18	18.32	23	28.28
1.4			25	26.44	27	20.76
1.5			26	27.28	31	28.68
1.6					24	14.8
1.7					21	20.84
1.8					26	18.84
1.9					23	15
2.0					21	15.84
2.1					29	18
2.2					23	18.52
2.3					30	31.8
2.4					26	20.16

K2-3

Kromdraai Mine		
Main HR Segment	100	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose Material	3	2
Stoniness - fixed	3	2
Sum Degree x Extent		29

Kromdraai Colliery		
Main HR Segment	200	
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	1	2
Sum Degree x Extent		24

Kromdraai Colliery		
Main HR Segment	300	
	Degree	Extent
Potholes	3	3
Corrugations	1	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	3	2
Sum Degree x Extent		25

Kromdraai Mine		
Main HR Segment	400	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		22

K2-4

Kromdraai Colliery		
Main HR Segment	500	
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		24

Kromdraai Colliery		
Main HR Segment	600	
	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		23

Kromdraai Mine		
Main HR Segment	700	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		21

Kromdraai Colliery		
Main HR Segment	800	
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		23

K2-5

Kromdraai Colliery		
Main HR Segment	900	
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	2	3
Loose Material	2	4
Stoniness - fixed	2	1
Sum Degree x Extent		22

Kromdraai Colliery	Main HR
Segment	Comment
100	Junction tip
900	Junction HR1 and 2

K2-6

Kromdraai Colliery		
HR1 Segment	**100**	
	Degree	**Extent**
Potholes	1	1
Corrugations	1	2
Rutting	1	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**14**

Kromdraai Colliery		
HR1 Segment	**200**	
	Degree	**Extent**
Potholes	1	1
Corrugations	1	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**16**

Kromdraai Colliery		
HR1 Segment	**300**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	1	2
Sum Degree x Extent		**18**

Kromdraai Colliery		
HR1 Segment	**400**	
	Degree	**Extent**
Potholes	2	1
Corrugations	2	2
Rutting	2	1
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**17**

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K2-7

Kromdraai Colliery		
HR1 Segment	500	
	Degree	Extent
Potholes	1	1
Corrugations	2	3
Rutting	2	2
Loose Material	2	5
Stoniness - fixed	1	1
Sum Degree x Extent		**22**

Kromdraai Colliery		
HR1 Segment	600	
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	2
Loose Material	2	5
Stoniness - fixed	1	1
Sum Degree x Extent		**20**

Kromdraai Colliery		
HR1 Segment	700	
	Degree	Extent
Potholes	1	1
Corrugations	2	3
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		**14**

Kromdraai Colliery		
HR1 Segment	800	
	Degree	Extent
Potholes	1	1
Corrugations	2	3
Rutting	1	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**18**

K2-8

Kromdraai Colliery		
HR1 Segment	**900**	
	Degree	**Extent**
Potholes	1	1
Corrugations	2	2
Rutting	2	1
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**16**

Kromdraai Colliery		
HR1 Segment	**1000**	
	Degree	**Extent**
Potholes	1	2
Corrugations	2	2
Rutting	2	1
Loose Material	2	5
Stoniness - fixed	1	1
Sum Degree x Extent		**19**

Kromdraai Colliery		
HR1 Segment	**1100**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	1	1
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**18**

Kromdraai Colliery		
HR1 Segment	**1200**	
	Degree	**Extent**
Potholes	1	2
Corrugations	2	2
Rutting	2	1
Loose Material	2	4
Stoniness - fixed	2	1
Sum Degree x Extent		**18**

K2-9

Kromdraai Colliery		
HR1 Segment	1300	
	Degree	Extent
Potholes	1	2
Corrugations	2	2
Rutting	2	1
Loose Material	2	4
Stoniness - fixed	2	1
Sum Degree x Extent		18

Kromdraai Colliery		
HR1 Segment	1400	
	Degree	Extent
Potholes	1	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	4
Stoniness - fixed	2	2
Sum Degree x Extent		25

Kromdraai Colliery		
HR1 Segment	1500	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose Material	2	4
Stoniness - fixed	2	2
Sum Degree x Extent		26

Kromdraai Colliery	HR1
Segment	Comment
100	Junction HR2
1400	Junction
1500	Junction

K2-10

Kromdraai Colliery		
HR2 Segment	**100**	
	Degree	**Extent**
Potholes	1	1
Corrugations	1	1
Rutting	2	1
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**11**

Kromdraai Colliery		
HR2 Segment	**200**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose Material	2	4
Stoniness - fixed	2	2
Sum Degree x Extent		**26**

Kromdraai Colliery		
HR2 Segment	**300**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	1	2
Sum Degree x Extent		**20**

Kromdraai Colliery		
HR2 Segment	**400**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		**22**

K2-11

Kromdraai Colliery		
HR2 Segment	500	
	Degree	Extent
Potholes	2	1
Corrugations	2	3
Rutting	2	2
Loose Material	1	3
Stoniness - fixed	1	1
Sum Degree x Extent		16

Kromdraai Colliery		
HR2 Segment	600	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	1	3
Sum Degree x Extent		26

Kromdraai Colliery		
HR2 Segment	700	
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	2	2
Sum Degree x Extent		26

Kromdraai Colliery		
HR2 Segment	800	
	Degree	Extent
Potholes	2	1
Corrugations	2	1
Rutting	3	2
Loose Material	1	4
Stoniness - fixed	1	1
Sum Degree x Extent		15

K2-12

Kromdraai Colliery		
HR2 Segment	900	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**21**

Kromdraai Colliery		
HR2 Segment	1000	
	Degree	Extent
Potholes	2	2
Corrugations	3	3
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	2	2
Sum Degree x Extent		**29**

Kromdraai Colliery		
HR2 Segment	1100	
	Degree	Extent
Potholes	3	3
Corrugations	3	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	2	2
Sum Degree x Extent		**31**

Kromdraai Colliery		
HR2 Segment	1200	
	Degree	Extent
Potholes	2	2
Corrugations	3	3
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**30**

K2-13

Kromdraai Colliery		
HR2 Segment	1300	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		23

Kromdraai Colliery		
HR2 Segment	1400	
	Degree	Extent
Potholes	3	2
Corrugations	2	3
Rutting	2	2
Loose Material	2	5
Stoniness - fixed	1	1
Sum Degree x Extent		27

Kromdraai Colliery		
HR2 Segment	1500	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		31

Kromdraai Colliery		
HR2 Segment	1600	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	3	2
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		24

K2-14

Kromdraai Colliery		
HR2 Segment	**1700**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	3	2
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**21**

Kromdraai Colliery		
HR2 Segment	**1800**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**26**

Kromdraai Colliery		
HR2 Segment	**1900**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	3	2
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**23**

Kromdraai Colliery		
HR2 Segment	**2000**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**21**

K2-15

Kromdraai Colliery		
HR2 Segment	**2100**	
	Degree	**Extent**
Potholes	2	2
Corrugations	3	3
Rutting	2	2
Loose Material	2	5
Stoniness - fixed	1	2
Sum Degree x Extent		**29**

Kromdraai Colliery		
HR2 Segment	**2200**	
	Degree	**Extent**
Potholes	3	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**23**

Kromdraai Colliery		
HR2 Segment	**2300**	
	Degree	**Extent**
Potholes	3	2
Corrugations	3	3
Rutting	2	2
Loose Material	2	5
Stoniness - fixed	1	1
Sum Degree x Extent		**30**

Kromdraai Colliery		
HR2 Segment	**2400**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**26**

K2-16

Kromdraai Colliery	**HR2**
SEGMENT	
0	**Pit end start**
500	**Bend**
600	**Bend**
2500	**Bend Join HR1**

APPENDIX K3

RESULTS OF HAUL ROAD SUBJECTIVE ROUGHNESS EVALUATIONS NEW VAAL COLLIERY

K3-2

SUMMARY OF RESULTS, MAXIMUM AVERAGE SECTION IRI (m/km) ROUGHNESS SCORE WITH SUBJECTIVE EVALUATION OF ROUGHNESS

New Vaal Mine

km	Main HR	IRI(x4)	Ramp 5	IRI(x4)	Ramp 3	IRI(x4)
0.1	23	26.68	24	26.68	25	23.64
0.2	14	28.48	26	28.48	22	21.68
0.3	18	19.04	20	19.04	38	28.36
0.4	20	20.28	22	20.28	52	24.20
0.5	21	17.32	20	17.32	56	52.28
0.6	21	18.68	19	18.68	52	47.36
0.7	18	17.40	18		51	37.40
0.8	18	17.12				
0.9	18	17.48				
1.0	18	19.36				
1.1	17	17.36				
1.2	17	16.24				
1.3	16	17.56				
1.4	20	16.48				
1.5	20	20.16				
1.6	22	18.32				
1.7	26	28.00				
1.8	19	20.32				
1.9	12	16.68				
2.0	21	20.36				
2.1	18	23.60				
2.2	16	18.56				
2.3	26	33.08				
2.4	22	13.36				
2.5	20	12.84				
2.6	20	13.08				
2.7	20	19.88				
2.8	22	14.56				
2.9	24	21.60				
3.0	22	24.20				
3.1	17	21.28				
3.2	19	20.28				
3.3	16	16.80				

K3-3

SUMMARY OF RESULTS, MAXIMUM AVERAGE SECTION IRI (m/km) ROUGHNESS SCORE WITH SUBJECTIVE EVALUATION OF ROUGHNESS
New Vaal Mine

km	Main HR	IRI(x4)	Ramp 5	IRI(x4)	Ramp 3	IRI(x4)
3.4	16	16.56				
3.5	18	15.08				
3.6	20	17.40				
3.7	16	17.88				
3.8	22	15.80				
3.9	23	28.16				
4.0	25	18.88				
4.1	20	15.24				
4.2	18	21.40				
4.3	18	26.12				
4.4	26	31.88				
4.5	21	21.44				
4.6	21	21.72				
4.7	21	21.04				
4.8	22	19.12				
4.9	22	20.76				
5.0	24	19.64				

K3-4

New Vaal Mine		
Main HR Segment	100	
	Degree	Extent
Potholes	2	4
Corrugations	1	1
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	2
Sum Degree x Extent		23

New Vaal Mine		
Main HR Segment	200	
	Degree	Extent
Potholes	1	1
Corrugations	1	1
Rutting	1	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		14

New Vaal Mine		
Main HR Segment	300	
	Degree	Extent
Potholes	3	3
Corrugations	1	1
Rutting	2	1
Loose Material	2	2
Stoniness - fixed	2	1
Sum Degree x Extent		18

New Vaal Mine		
Main HR Segment	400	
	Degree	Extent
Potholes	3	3
Corrugations	2	3
Rutting	1	1
Loose Material	2	1
Stoniness - fixed	2	1
Sum Degree x Extent		20

K3-5

New Vaal Mine		
Main HR Segment	500	
	Degree	Extent
Potholes	3	2
Corrugations	2	3
Rutting	1	1
Loose Material	2	3
Stoniness - fixed	2	1
Sum Degree x Extent		**21**

New Vaal Mine		
Main HR Segment	600	
	Degree	Extent
Potholes	3	2
Corrugations	2	3
Rutting	1	2
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**21**

New Vaal Mine		
Main HR Segment	700	
	Degree	Extent
Potholes	2	3
Corrugations	2	3
Rutting	1	1
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		**18**

New Vaal Mine		
Main HR Segment	800	
	Degree	Extent
Potholes	2	3
Corrugations	2	3
Rutting	1	1
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		**18**

K3-6

New Vaal Mine		
Main HR Segment	900	
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	1	1
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		18

New Vaal Mine		
Main HR Segment	1000	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	1
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		18

New Vaal Mine		
Main HR Segment	1100	
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	1	1
Loose Material	3	2
Stoniness - fixed	2	2
Sum Degree x Extent		17

New Vaal Mine		
Main HR Segment	1200	
	Degree	Extent
Potholes	2	2
Corrugations	1	1
Rutting	2	1
Loose Material	3	2
Stoniness - fixed	2	2
Sum Degree x Extent		17

K3-7

New Vaal Mine		
Main HR Segment	1300	
	Degree	Extent
Potholes	2	2
Corrugations	1	1
Rutting	2	1
Loose Material	3	2
Stoniness - fixed	1	3
Sum Degree x Extent		**16**

New Vaal Mine		
Main HR Segment	1400	
	Degree	Extent
Potholes	1	2
Corrugations	2	1
Rutting	2	2
Loose Material	3	2
Stoniness - fixed	2	3
Sum Degree x Extent		**20**

New Vaal Mine		
Main HR Segment	1500	
	Degree	Extent
Potholes	1	2
Corrugations	2	2
Rutting	3	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**20**

New Vaal Mine		
Main HR Segment	1600	
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**22**

K3-8

New Vaal Mine		
Main HR Segment	**1700**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose Material	3	2
Stoniness - fixed	3	2
Sum Degree x Extent		**26**

New Vaal Mine		
Main HR Segment	**1800**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	1
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**19**

New Vaal Mine		
Main HR Segment	**1900**	
	Degree	**Extent**
Potholes	2	2
Corrugations	1	1
Rutting	1	2
Loose Material	1	1
Stoniness - fixed	2	2
Sum Degree x Extent		**12**

New Vaal Mine		
Main HR Segment	**2000**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	1	1
Loose Material	3	2
Stoniness - fixed	2	3
Sum Degree x Extent		**21**

K3-9

New Vaal Mine		
Main HR Segment	2100	
	Degree	Extent
Potholes	2	2
Corrugations	1	1
Rutting	1	1
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		18

New Vaal Mine		
Main HR Segment	2200	
	Degree	Extent
Potholes	2	2
Corrugations	1	2
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		16

New Vaal Mine		
Main HR Segment	2300	
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		26

New Vaal Mine		
Main HR Segment	2400	
	Degree	Extent
Potholes	2	3
Corrugations	1	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		22

K3-10

New Vaal Mine		
Main HR Segment	2500	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	1	1
Loose Material	1	2
Stoniness - fixed	2	2
Sum Degree x Extent		20

New Vaal Mine		
Main HR Segment	2600	
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	1
Stoniness - fixed	2	2
Sum Degree x Extent		20

New Vaal Mine		
Main HR Segment	2700	
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	1
Stoniness - fixed	2	2
Sum Degree x Extent		20

New Vaal Mine		
Main HR Segment	2800	
	Degree	Extent
Potholes	2	2
Corrugations	3	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		22

K3-11

New Vaal Mine		
Main HR Segment	**2900**	
	Degree	**Extent**
Potholes	2	2
Corrugations	3	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**24**

New Vaal Mine		
Main HR Segment	**3000**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	1	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**22**

New Vaal Mine		
Main HR Segment	**3100**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	1	1
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**17**

New Vaal Mine		
Main HR Segment	**3200**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	1	3
Loose Material	2	3
Stoniness - fixed	2	1
Sum Degree x Extent		**19**

K3-12

New Vaal Mine		
Main HR Segment	3300	
	Degree	Extent
Potholes	2	1
Corrugations	2	2
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		16

New Vaal Mine		
Main HR Segment	3400	
	Degree	Extent
Potholes	2	1
Corrugations	2	1
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		16

New Vaal Mine		
Main HR Segment	3500	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	1
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		18

New Vaal Mine		
Main HR Segment	3600	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	1
Sum Degree x Extent		20

K3-13

New Vaal Mine		
Main HR Segment	**3700**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	1	2
Loose Material	2	1
Stoniness - fixed	2	2
Sum Degree x Extent		**16**

New Vaal Mine		
Main HR Segment	**3800**	
	Degree	**Extent**
Potholes	3	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**22**

New Vaal Mine		
Main HR Segment	**3900**	
	Degree	**Extent**
Potholes	2	2
Corrugations	3	3
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**23**

New Vaal Mine		
Main HR Segment	**4000**	
	Degree	**Extent**
Potholes	2	2
Corrugations	3	3
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**25**

K3-14

New Vaal Mine		
Main HR Segment	4100	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	2	1
Sum Degree x Extent		20

New Vaal Mine		
Main HR Segment	4200	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	1
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		18

New Vaal Mine		
Main HR Segment	4300	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	1
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		18

New Vaal Mine		
Main HR Segment	4400	
	Degree	Extent
Potholes	2	3
Corrugations	2	3
Rutting	1	1
Loose Material	3	3
Stoniness - fixed	2	2
Sum Degree x Extent		26

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K3-15

New Vaal Mine		
Main HR Segment	**4500**	
	Degree	**Extent**
Potholes	2	2
Corrugations	3	1
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**21**

New Vaal Mine		
Main HR Segment	**4600**	
	Degree	**Extent**
Potholes	2	2
Corrugations	3	1
Rutting	2	1
Loose Material	2	4
Stoniness - fixed	2	2
Sum Degree x Extent		**21**

New Vaal Mine		
Main HR Segment	**4700**	
	Degree	**Extent**
Potholes	2	2
Corrugations	3	1
Rutting	2	1
Loose Material	2	4
Stoniness - fixed	2	2
Sum Degree x Extent		**21**

New Vaal Mine		
Main HR Segment	**4800**	
	Degree	**Extent**
Potholes	2	1
Corrugations	2	1
Rutting	2	1
Loose Material	2	4
Stoniness - fixed	2	4
Sum Degree x Extent		**22**

K3-16

New Vaal Mine		
Main HR Segment	4900	
	Degree	Extent
Potholes	2	1
Corrugations	2	1
Rutting	2	1
Loose Material	2	4
Stoniness - fixed	2	4
Sum Degree x Extent		22

New Vaal Mine		
Main HR Segment	5000	
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	2	1
Loose Material	2	4
Stoniness - fixed	2	4
Sum Degree x Extent		24

New Vaal Mine	Main haul road
Segment	Comment
0m	Tip junction
400m	Ramp 1 junction
1500m	Bend
1700m	Ramp 2 junction
2100m	Hard park junction
3000m	Ramp 3 junction
3600m	Bend
3700m	Ramp 4/5 junction
4400m	Ramp 6 junction
5000m	Single lane
5037m	End

K3-17

New Vaal Mine		
Ramp 6 Segment	**100**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose Material	3	2
Stoniness - fixed	2	2
Sum Degree x Extent		**24**

New Vaal Mine		
Ramp 6 Segment	**200**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**26**

New Vaal Mine		
Ramp 6 Segment	**300**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**20**

New Vaal Mine		
Ramp 6 Segment	**400**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**22**

K3-18

New Vaal Mine		
Ramp 6 Segment	**500**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**20**

New Vaal Mine		
Ramp 3 Segment	**600**	
	Degree	**Extent**
Potholes	4	3
Corrugations	2	4
Rutting	4	3
Loose Material	2	4
Stoniness - fixed	4	3
Sum Degree x Extent		**52**

New Vaal Mine		
Ramp 3 Segment	**700**	
	Degree	**Extent**
Potholes	4	2
Corrugations	3	2
Rutting	3	3
Loose Material	3	4
Stoniness - fixed	4	4
Sum Degree x Extent		**51**

New Vaal Mine	**Ramp 3**
Segment	**Comment**
300m	Ramp 7 junction
600m	Bend
700m	Bend
751m	End

K3-19

New Vaal Mine		
Ramp 3 Segment	**100**	
	Degree	**Extent**
Potholes	3	1
Corrugations	1	1
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	3	2
Sum Degree x Extent		**25**

New Vaal Mine		
Ramp 3 Segment	**200**	
	Degree	**Extent**
Potholes	2	1
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**22**

New Vaal Mine		
Ramp 3 Segment	**300**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	2
Rutting	2	2
Loose Material	4	3
Stoniness - fixed	3	3
Sum Degree x Extent		**38**

New Vaal Mine		
Ramp 3 Segment	**400**	
	Degree	**Extent**
Potholes	3	4
Corrugations	4	2
Rutting	4	4
Loose Material	3	4
Stoniness - fixed	2	2
Sum Degree x Extent		**52**

K3-20

New Vaal Mine		
Ramp 3 Segment	**500**	
	Degree	**Extent**
Potholes	4	2
Corrugations	3	4
Rutting	4	3
Loose Material	4	4
Stoniness - fixed	4	2
Sum Degree x Extent		**56**

New Vaal Mine		
Ramp 3 Segment	**600**	
	Degree	**Extent**
Potholes	4	3
Corrugations	2	4
Rutting	4	3
Loose Material	2	4
Stoniness - fixed	4	3
Sum Degree x Extent		**52**

New Vaal Mine		
Ramp 3 Segment	**700**	
	Degree	**Extent**
Potholes	4	2
Corrugations	3	2
Rutting	3	3
Loose Material	3	4
Stoniness - fixed	4	4
Sum Degree x Extent		**51**

New Vaal Mine	**Ramp 3**
Segment	**Comment**
600m	Downhill steep
700m	End

APPENDIX K4

RESULTS OF HAUL ROAD SUBJECTIVE ROUGHNESS EVALUATIONS KLEINKOPJE COLLIERY

SUMMARY OF RESULTS, MAXIMUM AVERAGE IRI (m/km) ROUGHNESS SCORE WITH SUBJECTIVE EVALUATION OF ROUGHNESS

Kleinkopje Colliery

km	3A	IRI(x4)	2A	IRI(x4)	Ramp 13/14	IRI(x4)	5W	IRI(x4)
0.1	22	20.16	44	27.04	32	28.32	24	23.68
0.2	16	17.08	31	44.08	34	26.68	24	26.64
0.3	15	19.56	31	22.16	36	32.84	28	21.80
0.4	15	19.08	31	21.6	38	43.32	19	17.92
0.5	20	19.08	29	22.56	33	40.32	17	17.24
0.6	26	28.8	17	21.64	34	33.32	20	17.16
0.7	26	25.32	18	20.64	33	38.2	17	15.00
0.8	24	24.36	13	22.28	31	36.16	13	15.68
0.9	27	24.2	24	32.24	31	24.04	23	16.08
1.0	23	19.72	14	19.68	32	25.44	27	14.16
1.1	30	22.92	15	19.92	22	22.48	23	20.96
1.2	32	26	18	27.2	22	25.8	24	16.36
1.3	32	35.28	15	21.44	21	23.12	22	18.52
1.4	25	24.08	12	16.48	24	28.32	17	13.80
1.5	18	23.8	10	14.44	33	22.4	15	16.72
1.6	31	41.2	12	18.64	31	27.2	24	22.52
1.7	24	23.8	12	16.72	32	26.44	22	31.04
1.8	24	26.32	20	22.72	35	29.32	20	21.44
1.9	34	31.36	12	21.4	28	36.72	20	24.80
2.0	31	33.92	17	18.04	26	35.64	34	27.76
2.1	22	29.16	16	15.28	27	30.52	15	24.88
2.2	22	28.96	16	12.28	22	31.4	20	18.68
2.3	22	27.68	19	16.52	27	33.36	19	19.12
2.4	23	36	19	15.08	24	61.64	29	32.64
2.5	26	33.48	19	21.4			34	37.88
2.6	27		19	23.16			37	32.44
2.7			16	19.04			47	39.64
2.8			19	25.08			39	34.00

K4-3

Kleinkopje Colliery		
3A Segment	100	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**22**

Kleinkopje Colliery		
3A Segment	200	
	Degree	Extent
Potholes	1	2
Corrugations	2	2
Rutting	2	2
Loose Material	1	2
Stoniness - fixed	2	2
Sum Degree x Extent		**16**

Kleinkopje Colliery		
3A Segment	300	
	Degree	Extent
Potholes	2	2
Corrugations	1	1
Rutting	2	2
Loose Material	2	1
Stoniness - fixed	2	2
Sum Degree x Extent		**15**

Kleinkopje Colliery		
3A Segment	400	
	Degree	Extent
Potholes	2	2
Corrugations	1	1
Rutting	2	2
Loose Material	1	2
Stoniness - fixed	2	2
Sum Degree x Extent		**15**

K4-4

Kleinkopje Colliery		
3A Segment	**500**	
	Degree	**Extent**
Potholes	2	2
Corrugations	1	2
Rutting	2	2
Loose Material	1	4
Stoniness - fixed	2	3
Sum Degree x Extent		**20**

Kleinkopje Colliery		
3A Segment	**600**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	3
Rutting	2	2
Loose Material	1	4
Stoniness - fixed	2	3
Sum Degree x Extent		**26**

Kleinkopje Colliery		
3A Segment	**700**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	2	3
Sum Degree x Extent		**26**

Kleinkopje Colliery		
3A Segment	**800**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**24**

K4-5

Kleinkopje Colliery		
3A Segment	**900**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	3	3
Stoniness - fixed	2	3
Sum Degree x Extent		**27**

Kleinkopje Colliery		
3A Segment	**1000**	
	Degree	**Extent**
Potholes	1	2
Corrugations	1	2
Rutting	2	2
Loose Material	3	2
Stoniness - fixed	3	3
Sum Degree x Extent		**23**

Kleinkopje Colliery		
3A Segment	**1100**	
	Degree	**Extent**
Potholes	2	2
Corrugations	1	3
Rutting	1	2
Loose Material	3	4
Stoniness - fixed	3	3
Sum Degree x Extent		**30**

Kleinkopje Colliery		
3A Segment	**1200**	
	Degree	**Extent**
Potholes	3	2
Corrugations	2	2
Rutting	2	2
Loose Material	3	4
Stoniness - fixed	2	3
Sum Degree x Extent		**32**

K4-6

Kleinkopje Colliery		
3A Segment	1300	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	2	2
Loose Material	3	3
Stoniness - fixed	2	3
Sum Degree x Extent		32

Kleinkopje Colliery		
3A Segment	1400	
	Degree	Extent
Potholes	3	1
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	3	2
Sum Degree x Extent		25

Kleinkopje Colliery		
3A Segment	1500	
	Degree	Extent
Potholes	1	2
Corrugations	2	1
Rutting	2	1
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		18

Kleinkopje Colliery		
3A Segment	1600	
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	3	2
Loose Material	2	3
Stoniness - fixed	3	3
Sum Degree x Extent		31

K4-7

Kleinkopje Colliery		
3A Segment	**1700**	
	Degree	**Extent**
Potholes	3	1
Corrugations	1	2
Rutting	2	2
Loose Material	3	3
Stoniness - fixed	3	2
Sum Degree x Extent		**24**

Kleinkopje Colliery		
3A Segment	**1800**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**24**

Kleinkopje Colliery		
3A Segment	**1900**	
	Degree	**Extent**
Potholes	3	2
Corrugations	2	2
Rutting	2	3
Loose Material	3	4
Stoniness - fixed	3	2
Sum Degree x Extent		**34**

Kleinkopje Colliery		
3A Segment	**2000**	
	Degree	**Extent**
Potholes	2	4
Corrugations	2	2
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	3	3
Sum Degree x Extent		**31**

K4-8

Kleinkopje Colliery		
3A Segment	2100	
	Degree	Extent
Potholes	2	1
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		22

Kleinkopje Colliery		
3A Segment	2200	
	Degree	Extent
Potholes	2	2
Corrugations	2	3
Rutting	2	1
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		22

Kleinkopje Colliery		
3A Segment	2300	
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		22

Kleinkopje Colliery		
3A Segment	2400	
	Degree	Extent
Potholes	2	3
Corrugations	1	3
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		23

K4-9

Kleinkopje Colliery		
3A Segment	2500	
	Degree	Extent
Potholes	2	3
Corrugations	2	3
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		26

Kleinkopje Colliery		
3A Segment	2600	
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	3	2
Loose Material	3	3
Stoniness - fixed	2	3
Sum Degree x Extent		27

Kleinkopje Colliery	3A
Segment	Comment
0	At tip
500	Junction
700	Junction
1400	Wet patch potholes
1700	Wet patch at junction
2300	Wet

K4-10

Kleinkopje Colliery		
2A Segment	**100**	
	Degree	**Extent**
Potholes	4	3
Corrugations	3	2
Rutting	3	4
Loose Material	2	3
Stoniness - fixed	2	4
Sum Degree x Extent		**44**

Kleinkopje Colliery		
2A Segment	**200**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**31**

Kleinkopje Colliery		
2A Segment	**300**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**31**

Kleinkopje Colliery		
2A Segment	**400**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**31**

K4-11

Kleinkopje Colliery		
2A Segment	**500**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose Material	3	3
Stoniness - fixed	2	3
Sum Degree x Extent		**29**

Kleinkopje Colliery		
2A Segment	**600**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	1
Rutting	1	1
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**17**

Kleinkopje Colliery		
2A Segment	**700**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**18**

Kleinkopje Colliery		
2A Segment	**800**	
	Degree	**Extent**
Potholes	3	2
Corrugations	1	1
Rutting	2	1
Loose Material	1	2
Stoniness - fixed	1	2
Sum Degree x Extent		**13**

K4-12

Kleinkopje Colliery		
2A Segment	900	
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose Material	3	2
Stoniness - fixed	2	2
Sum Degree x Extent		24

Kleinkopje Colliery		
2A Segment	1000	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	1	1
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		14

Kleinkopje Colliery		
2A Segment	1100	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		15

Kleinkopje Colliery		
2A Segment	1200	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		18

K4-13

Kleinkopje Colliery		
2A Segment	1300	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	1	1
Loose Material	2	2
Stoniness - fixed	2	1
Sum Degree x Extent		15

Kleinkopje Colliery		
2A Segment	1400	
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		12

Kleinkopje Colliery		
2A Segment	1500	
	Degree	Extent
Potholes	1	1
Corrugations	2	1
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		10

Kleinkopje Colliery		
2A Segment	1600	
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	1
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		12

K4-14

Kleinkopje Colliery		
2A Segment	**1700**	
	Degree	**Extent**
Potholes	1	1
Corrugations	2	2
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		**12**

Kleinkopje Colliery		
2A Segment	**1800**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**20**

Kleinkopje Colliery		
2A Segment	**1900**	
	Degree	**Extent**
Potholes	1	1
Corrugations	2	1
Rutting	1	2
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**12**

Kleinkopje Colliery		
2A Segment	**2000**	
	Degree	**Extent**
Potholes	2	2
Corrugations	1	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**17**

K4-15

Kleinkopje Colliery		
2A Segment	2100	
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**16**

Kleinkopje Colliery		
2A Segment	2200	
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**16**

Kleinkopje Colliery		
2A Segment	2300	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	2	1
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**19**

Kleinkopje Colliery		
2A Segment	2400	
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**19**

K4-16

Kleinkopje Colliery		
2A Segment	**2500**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	1
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**19**

Kleinkopje Colliery		
2A Segment	**2600**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	1
Rutting	1	2
Loose Material	2	4
Stoniness - fixed	1	1
Sum Degree x Extent		**19**

Kleinkopje Colliery		
2A Segment	**2700**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	1	1
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		**16**

Kleinkopje Colliery		
2A Segment	**2800**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	3
Rutting	1	2
Loose Material	2	3
Stoniness - fixed	1	1
Sum Degree x Extent		**19**

K4-17

Kleinkopje Colliery		
2A Segment	**2900**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	3
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	1	1
Sum Degree x Extent		**22**

Kleinkopje Colliery	**2A**
Segment	**Comment**
0	Tip
100	Tip approach
200	5W junction
500	Junction
800	Junction
1200	Bend
2600	Junction
2900	Junction Ramp

K4-18

Kleinkopje Colliery		
Ramp 13/14 Segment	**100**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	3	4
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**32**

Kleinkopje Colliery		
Ramp 13/14 Segment	**200**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	2	4
Sum Degree x Extent		**34**

Kleinkopje Colliery		
Ramp 13/14 Segment	**300**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	2
Rutting	3	3
Loose Material	3	2
Stoniness - fixed	2	4
Sum Degree x Extent		**36**

Kleinkopje Colliery		
Ramp 13/14 Segment	**400**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	3
Rutting	3	3
Loose Material	3	2
Stoniness - fixed	2	4
Sum Degree x Extent		**38**

K4-19

Kleinkopje Colliery		
Ramp 13/14 Segment	500	
	Degree	Extent
Potholes	2	4
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		33

Kleinkopje Colliery		
Ramp 13/14 Segment	600	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		34

Kleinkopje Colliery		
Ramp 13/14 Segment	700	
	Degree	Extent
Potholes	3	3
Corrugations	3	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		33

Kleinkopje Colliery		
Ramp 13/14 Segment	800	
	Degree	Extent
Potholes	3	3
Corrugations	3	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		31

K4-20

Kleinkopje Colliery		
Ramp 13/14 Segment	**900**	
	Degree	**Extent**
Potholes	3	3
Corrugations	2	3
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	2	3
Sum Degree x Extent		**31**

Kleinkopje Colliery		
Ramp 13/14 Segment	**1000**	
	Degree	**Extent**
Potholes	3	4
Corrugations	2	3
Rutting	2	3
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**32**

Kleinkopje Colliery		
Ramp 13/14 Segment	**1100**	
	Degree	**Extent**
Potholes	1	2
Corrugations	2	2
Rutting	2	1
Loose Material	3	4
Stoniness - fixed	2	1
Sum Degree x Extent		**22**

Kleinkopje Colliery		
Ramp 13/14 Segment	**1200**	
	Degree	**Extent**
Potholes	1	2
Corrugations	2	2
Rutting	2	1
Loose Material	3	4
Stoniness - fixed	2	1
Sum Degree x Extent		**22**

K4-21

Kleinkopje Colliery		
Ramp 13/14 Segment	1300	
	Degree	Extent
Potholes	2	1
Corrugations	2	1
Rutting	2	2
Loose Material	3	3
Stoniness - fixed	2	2
Sum Degree x Extent		21

Kleinkopje Colliery		
Ramp 13/14 Segment	1400	
	Degree	Extent
Potholes	2	1
Corrugations	2	2
Rutting	3	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		24

Kleinkopje Colliery		
Ramp 13/14 Segment	1500	
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	2	4
Sum Degree x Extent		33

Kleinkopje Colliery		
Ramp 13/14 Segment	1600	
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	2	4
Sum Degree x Extent		31

K4-22

Kleinkopje Colliery		
Ramp 13/14 Segment	**1700**	
	Degree	**Extent**
Potholes	3	2
Corrugations	2	2
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	3	3
Sum Degree x Extent		**32**

Kleinkopje Colliery		
Ramp 13/14 Segment	**1800**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	3
Rutting	3	3
Loose Material	2	2
Stoniness - fixed	3	4
Sum Degree x Extent		**35**

Kleinkopje Colliery		
Ramp 13/14 Segment	**1900**	
	Degree	**Extent**
Potholes	3	2
Corrugations	2	1
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	4
Sum Degree x Extent		**28**

Kleinkopje Colliery		
Ramp 13/14 Segment	**2000**	
	Degree	**Extent**
Potholes	2	2
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**26**

K4-23

Kleinkopje Colliery		
Ramp 13/14 Segment	2100	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	2
Loose Material	3	3
Stoniness - fixed	2	2
Sum Degree x Extent		27

Kleinkopje Colliery		
Ramp 13/14 Segment	2200	
	Degree	Extent
Potholes	2	1
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		22

Kleinkopje Colliery		
Ramp 13/14 Segment	2300	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		27

Kleinkopje Colliery		
Ramp 13/14 Segment	2400	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		24

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K4-24

Kleinkopje Colliery		
5W Segment	100	
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	3	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		24

Kleinkopje Colliery		
5W Segment	200	
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	3	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		24

Kleinkopje Colliery		
5W Segment	300	
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	2	2
Loose Material	3	4
Stoniness - fixed	2	3
Sum Degree x Extent		28

Kleinkopje Colliery		
5W Segment	400	
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		19

K4-25

Kleinkopje Colliery		
5W Segment	**500**	
	Degree	**Extent**
Potholes	1	1
Corrugations	2	2
Rutting	2	2
Loose Material	1	2
Stoniness - fixed	2	3
Sum Degree x Extent		**17**

Kleinkopje Colliery		
5W Segment	**600**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	1
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**20**

Kleinkopje Colliery		
5W Segment	**700**	
	Degree	**Extent**
Potholes	1	1
Corrugations	2	2
Rutting	1	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**17**

Kleinkopje Colliery		
5W Segment	**800**	
	Degree	**Extent**
Potholes	1	2
Corrugations	2	2
Rutting	1	1
Loose Material	2	2
Stoniness - fixed	1	2
Sum Degree x Extent		**13**

K4-26

Kleinkopje Colliery		
5W Segment	900	
	Degree	Extent
Potholes	3	2
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	1	3
Sum Degree x Extent		**23**

Kleinkopje Colliery		
5W Segment	1000	
	Degree	Extent
Potholes	2	3
Corrugations	2	2
Rutting	2	1
Loose Material	2	3
Stoniness - fixed	3	3
Sum Degree x Extent		**27**

Kleinkopje Colliery		
5W Segment	1100	
	Degree	Extent
Potholes	2	2
Corrugations	1	2
Rutting	2	1
Loose Material	2	3
Stoniness - fixed	3	3
Sum Degree x Extent		**23**

Kleinkopje Colliery		
5W Segment	1200	
	Degree	Extent
Potholes	2	2
Corrugations	1	2
Rutting	2	2
Loose Material	2	4
Stoniness - fixed	2	3
Sum Degree x Extent		**24**

K4-27

Kleinkopje Colliery		
5W Segment	1300	
	Degree	Extent
Potholes	2	2
Corrugations	1	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**22**

Kleinkopje Colliery		
5W Segment	1400	
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	2	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**17**

Kleinkopje Colliery		
5W Segment	1500	
	Degree	Extent
Potholes	1	1
Corrugations	2	2
Rutting	1	2
Loose Material	2	2
Stoniness - fixed	2	2
Sum Degree x Extent		**15**

Kleinkopje Colliery		
5W Segment	1600	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	3	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**24**

K4-28

Kleinkopje Colliery		
5W Segment	1700	
	Degree	Extent
Potholes	2	2
Corrugations	2	1
Rutting	3	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**22**

Kleinkopje Colliery		
5W Segment	1800	
	Degree	Extent
Potholes	2	2
Corrugations	2	2
Rutting	1	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**20**

Kleinkopje Colliery		
5W Segment	1900	
	Degree	Extent
Potholes	2	2
Corrugations	1	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	1	2
Sum Degree x Extent		**20**

Kleinkopje Colliery		
5W Segment	2000	
	Degree	Extent
Potholes	3	3
Corrugations	2	2
Rutting	2	3
Loose Material	2	3
Stoniness - fixed	3	3
Sum Degree x Extent		**34**

K4-29

Kleinkopje Colliery		
5W Segment	**2100**	
	Degree	**Extent**
Potholes	2	1
Corrugations	2	1
Rutting	1	1
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**15**

Kleinkopje Colliery		
5W Segment	**2200**	
	Degree	**Extent**
Potholes	2	1
Corrugations	2	1
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**20**

Kleinkopje Colliery		
5W Segment	**2300**	
	Degree	**Extent**
Potholes	1	1
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	2	2
Sum Degree x Extent		**19**

Kleinkopje Colliery		
5W Segment	**2400**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	2	2
Loose Material	2	3
Stoniness - fixed	3	3
Sum Degree x Extent		**29**

K4-30

Kleinkopje Colliery		
5W Segment	**2500**	
	Degree	**Extent**
	3	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**34**

Kleinkopje Colliery		
5W Segment	**2600**	
	Degree	**Extent**
Potholes	4	3
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	2	3
Sum Degree x Extent		**37**

Kleinkopje Colliery		
5W Segment	**2700**	
	Degree	**Extent**
Potholes	2	3
Corrugations	2	2
Rutting	3	3
Loose Material	3	4
Stoniness - fixed	4	4
Sum Degree x Extent		**47**

Kleinkopje Colliery		
5W Segment	**2800**	
	Degree	**Extent**
Potholes	2	4
Corrugations	2	2
Rutting	3	3
Loose Material	2	3
Stoniness - fixed	3	4
Sum Degree x Extent		**39**

APPENDIX L

RESULTS AND ANALYSIS OF ROLLING RESISTANCE TESTS

Contents

Summary of rolling resistance tests, test vehicle specifications and individual test site rolling resistance data for the mine sites;

Kriel Colliery main haul road and ramp 7 road
Kromdraai Colliery main haul road and HR2 road
New Vaal Colliery main haul road at ramp 3 turnoff and end, ramp 3
Kleinkopje Colliery 2A road and discards road

ROLLING RESISTANCE CORRELATION WITH SUBJECTIVE EVALUATION OF ROAD ROUGHNESS - SUMMARY OF RESULTS

		Average	Rolling resistance (N/kg) from linear regression (RR/speed) of individual site data		
Site	**Segment**	**Evaluation score**	**20km/h**	**30km/h**	**40km/h**
Kleinkopje Colliery 2A road	1600 - 1850m	10	0.213	0.217	0.221
New Vaal Colliery main haul road (R3)	3200 - 3400m	20	0.214	0.233	0.253
Kromdraai Colliery haul road 2	785 - 1167m	31	0.235	0.256	0.273
New Vaal Colliery main haul road (end)	4600 - 4900m	23	0.184	0.221	0.258
Kromdraai Colliery main haul road	257 - 557m	23	0.187	0.210	0.233
Kriel Colliery main haul road	3400 - 3700m	47	0.262	0.295	0.328
New Vaal Colliery ramp 3	300 - 600m	60	0.296	0.319	0.342
Kriel Colliery ramp 7	900 - 1200m	83	0.266	0.282	0.298
Kleinkopje Colliery discards road	700 - 750m	74	0.272	0.287	0.314

ROLLING RESISTANCE ASSESSMENT
Kriel Colliery

ROAD	**Main haul road**
SEGMENT	**3400 - 3700m**
GRADE	**0.005**
GRADE RESISTANCE	**0.048**
VEHICLE	**Toyota Hilux LWB**
VEHICLE MASS	**1266 kg**
TYRE & PRESSURE FRONT	**190 R14C, 190 kPa**
TYRE & PRESSURE REAR	**190 R14C, 190 kPa**
CONSTANT SPEED DISTANCE (m)	**100**

Constant speed t (s)	**Deceleration**		**Direction**	**Constant speed (km/h)**	**Total resistance (N/kg) including grade**		**Rolling resistance (N/kg)**
	t1 (s)	**d1 (m)**			**Using t1**	**Using d1**	
27	14	26.5	up grade	13.333	0.265	0.259	0.211
18	21	59.2	up grade	20.000	0.265	0.261	0.213
13	19	86.2	up grade	27.692	0.405	0.343	0.296
10	28	147.7	up grade	36.000	0.357	0.339	0.291
8	33	214.3	up grade	45.000	0.379	0.365	0.317
25	16	35.5	down grade	14.400	0.250	0.225	0.273
20	22	61.1	down grade	18.000	0.227	0.205	0.252
13	28	100.3	down grade	27.692	0.275	0.295	0.343
11	30	137.4	down grade	32.727	0.303	0.301	0.348
7	44	320.2	down grade	51.429	0.325	0.319	0.366

ROLLING RESISTANCE ASSESSMENT
Kriel Colliery

ROAD	Ramp 7
SEGMENT	900 - 1200m
GRADE	0.016
GRADE RESISTANCE	0.161
VEHICLE	Toyota Hilux LWB
VEHICLE MASS	1266 kg
TYRE & PRESSURE FRONT	190 R14C, 190 kPa
TYRE & PRESSURE REAR	190 R14C, 190 kPa
CONSTANT SPEED DISTANCE (m)	100

Constant speed t (s)	Deceleration		Direction	Constant speed (km/h)	Total resistance (N/kg) including grade		Rolling resistance (N/kg)
	t1 (s)	d1 (m)			Using t1	Using d1	
25	10	20.4	up grade	14.400	0.400	0.392	0.232
18	14	40.0	up grade	20.000	0.397	0.386	0.225
14	17	59.0	up grade	25.714	0.420	0.432	0.272
10	23	117.0	up grade	36.000	0.435	0.427	0.267
8	29	185.6	up grade	45.000	0.431	0.421	0.260
27	28	63.2	down grade	13.333	0.132	0.109	0.269
20	37	92.4	down grade	18.000	0.135	0.135	0.296
13	44	196.6	down grade	27.692	0.175	0.150	0.311
11	59	278.3	down grade	32.727	0.154	0.148	0.309
8	64	423	down grade	45.000	0.195	0.185	0.345

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ROLLING RESISTANCE ASSESSMENT
Kromdraai Colliery

ROAD	Main haul road
SEGMENT	257 - 557m
GRADE	0.010
GRADE RESISTANCE	0.100
VEHICLE	Toyota Hilux LWB
VEHICLE MASS	1266 kg
TYRE & PRESSURE FRONT	190 R14C, 190 kPa
TYRE & PRESSURE REAR	190 R14C, 190 kPa
CONSTANT SPEED DISTANCE (m)	100

Constant speed t (s)	Deceleration		Direction	Constant speed (km/h)	Total resistance (N/kg) including grade		Rolling resistance (N/kg)
	t1 (s)	d1 (m)			Using t1	Using d1	
25	15	29.5	up grade	14.400	0.267	0.271	0.171
16	21	69.8	up grade	22.500	0.298	0.280	0.180
13	23	90.5	up grade	27.692	0.334	0.327	0.227
10	30	147.1	up grade	36.000	0.333	0.340	0.240
9	34	203.5	up grade	40.000	0.327	0.303	0.203
7	45	295.4	up grade	51.429	0.317	0.345	0.245
23	17	34.4	up grade	15.652	0.256	0.275	0.175
19	19	54.7	up grade	18.947	0.277	0.253	0.153
14	22	85.6	up grade	25.714	0.325	0.298	0.198
11	27	131.3	up grade	32.727	0.337	0.315	0.215
8	36	207.4	up grade	45.000	0.347	0.377	0.277

Constant speed t (s)	**Deceleration t1 (s)**	**Deceleration d1 (m)**	**Direction**	**Constant speed (km/h)**	**Using t1 (N/kg) including grade**	**Using d1 (N/kg) including grade**	**Rolling resistance (N/kg)**
7	43	282.6	up grade	51.429	0.332	0.361	0.261
27	92	104.6	down grade	13.333	0.040	0.066	0.166
28	76	109.1	down grade	12.857	0.047	0.058	0.159
29	47	78.3	down grade	12.414	0.073	0.076	0.176
30	36	58.1	down grade	12.000	0.093	0.096	0.196
30	45	71.4	down grade	12.000	0.074	0.078	0.178

ROLLING RESISTANCE ASSESSMENT
Kromdraai Colliery

ROAD	HR2
SEGMENT	785 - 1167m
GRADE	0.002
GRADE RESISTANCE	0.015
VEHICLE	Toyota Hilux LWB
VEHICLE MASS	1266 kg
TYRE & PRESSURE FRONT	190 R14C, 190 kPa
TYRE & PRESSURE REAR	190 R14C, 190 kPa
CONSTANT SPEED DISTANCE(m)	100

Constant speed t (s)	Deceleration		Direction	Constant speed (km/h)	Total resistance (N/kg) including grade		Rolling resistance (N/kg)
	t1 (s)	d1 (m)			Using t1	Using d1	
26	16	28.3	up grade	13.846	0.240	0.261	0.247
19	26	59.5	up grade	18.947	0.202	0.233	0.218
13	37	126.1	up grade	27.692	0.208	0.235	0.220
10	45	201.7	up grade	36.000	0.222	0.248	0.233
8	49	276.0	up grade	45.000	0.255	0.283	0.268
6	62	382.0	up grade	60.000	0.269	0.364	0.349
26	16	30.1	down grade	13.846	0.240	0.246	0.260
18	26	61.2	down grade	20.000	0.214	0.252	0.267
13	39	129.0	down grade	27.692	0.197	0.229	0.244
11	46	181.1	down grade	32.727	0.198	0.228	0.243
8	56	283.1	down grade	45.000	0.223	0.276	0.291
7	67	375.6	down grade	51.429	0.213	0.272	0.286

ROLLING RESISTANCE ASSESSMENT - New Vaal Colliery

ROAD	**Main haul road**
SEGMENT	**4600 - 4900m**
GRADE	**0.001**
GRADE RESISTANCE	**0.014**
VEHICLE	**Toyota Hilux LWB**
VEHICLE MASS	**1266 kg**
TYRE & PRESSURE FRONT	**190 R14C, 190 kPa**
TYRE & PRESSURE REAR	**190 R14C, 190 kPa**
CONSTANT SPEED DISTANCE(m)	**100**

Constant speed t (s)	**Deceleration**		**Direction**	**Constant speed (km/h)**	**Total resistance (N/kg) (including grade)**		**Rolling resistance (N/kg)**
	t1 (s)	**d1 (m)**			**Using t1**	**Using d1**	
25	33	56.6	up grade	14.400	0.121	0.141	0.128
21	27	77.7	up grade	17.143	0.176	0.146	0.132
15	36	94.2	up grade	24.000	0.185	0.236	0.222
11	49	148.0	up grade	32.727	0.186	0.279	0.266
9	52	235.2	up grade	40.000	0.214	0.262	0.249
6	77	427.4	up grade	60.000	0.216	0.325	0.311
30	29	48.4	down grade	12.000	0.115	0.115	0.128
20	30	70.8	down grade	18.000	0.167	0.177	0.190
15	33	117.7	down grade	24.000	0.202	0.189	0.202
10	54	184.6	down grade	36.000	0.185	0.271	0.285
8		237.6	down grade	45.000		0.329	0.342
5	95	623.6	down grade	72.000	0.211	0.321	0.334

ROLLING RESISTANCE ASSESSMENT
New Vaal Colliery

ROAD	**Ramp 3**
SEGMENT	**300 - 600m**
GRADE	**0.011**
GRADE RESISTANCE	**0.105**
VEHICLE	**Toyota Hilux LWB**
VEHICLE MASS	**1266 kg**
TYRE & PRESSURE FRONT	**190 R14C, 190 kPa**
TYRE & PRESSURE REAR	**190 R14C, 190 kPa**
CONSTANT SPEED DISTANCE (m)	**100**

Constant speed t (s)	Deceleration		Direction	Constant speed (km/h)	Total resistance (N/kg) including grade		Rolling resistance (N/kg)
	t1 (s)	d1 (m)			Using t1	Using d1	
27	17	36.7	up grade	13.333	0.218	0.187	0.292
23	20	54.3	up grade	15.652	0.217	0.174	0.279
14	28	126.0	up grade	25.714	0.255	0.202	0.307
10	37	222	up grade	36.000	0.270	0.225	0.330
9	40	255	up grade	40.000	0.278	0.242	0.347

ROLLING RESISTANCE ASSESSMENT
New Vaal Colliery

ROAD	Main haul road
SEGMENT	3200 - 3400m Ramp3 turn
GRADE	0.005
GRADE RESISTANCE	0.053
VEHICLE	Toyota Hilux LWB
VEHICLE MASS	1266 kg
TYRE & PRESSURE FRONT	190 R14C, 190 kPa
TYRE & PRESSURE REAR	190 R14C, 190 kPa
CONSTANT SPEED DISTANCE (m)	100

Constant speed t (s)	Deceleration		Direction	Constant speed (km/h)	Total resistance (N/kg) including grade		Rolling resistance (N/kg)
	t1 (s)	d1 (m)			Using t1	Using d1	
27	13	24.7	up grade	13.333	0.285	0.278	0.225
20	17	44.7	up grade	18.000	0.294	0.280	0.227
14	33	94.2	up grade	25.714	0.216	0.271	0.218
11	38	138.0	up grade	32.727	0.239	0.299	0.246
7	48	325.8	up grade	51.429	0.298	0.313	0.260
27	21	46.7	down grade	13.333	0.176	0.147	0.200
22	40	67.2	down grade	16.364	0.114	0.154	0.207
14	54	183.3	down grade	25.714	0.132	0.139	0.192
10	70	307.2	down grade	36.000	0.143	0.163	0.216
7	58	386.3	down grade	51.429	0.246	0.264	0.317

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ROLLING RESISTANCE ASSESSMENT
Kleinkopje Colliery

ROAD	2A
SEGMENT	1600 - 1850m
GRADE	0.000
GRADE RESISTANCE	0.004
VEHICLE	Toyota Hilux LWB
VEHICLE MASS	1266 kg
TYRE & PRESSURE FRONT	190 R14C, 190 kPa
TYRE & PRESSURE REAR	190 R14C, 190 kPa
CONSTANT SPEED DISTANCE (m)	100

Constant speed t (s)	Deceleration		Direction	Constant speed (km/h)	Total resistance (N/kg) including grade		Rolling resistance (N/kg)
	t1 (s)	d1 (m)			Using t1	Using d1	
26	19	34.2	up grade	13.846	0.202	0.216	0.212
24	19	39.1	up grade	15.000	0.219	0.222	0.218
19	24	59.1	up grade	18.947	0.219	0.234	0.230
19	20	52.3	up grade	18.947	0.263	0.265	0.260
13	36	131.6	up grade	27.692	0.214	0.225	0.220
13	38	135.5	up grade	27.692	0.202	0.218	0.214
11	42	180.3	up grade	32.727	0.216	0.229	0.225
11	46	189.4	up grade	32.727	0.198	0.218	0.214
26	33	42.7	down grade	13.846	0.117	0.173	0.178
29	23	31.8	down grade	12.414	0.150	0.187	0.191
20	29	58.8	down grade	18.000	0.172	0.213	0.217

Constant speed t (s)	Deceleration t1 (s)	Deceleration d1 (m)	Direction	Constant speed (km/h)	Using t1 (N/kg) including grade	Using d1 (N/kg) including grade	Rolling resistance (N/kg)
20	30	60	down grade	18.000	0.167	0.208	0.213
12	43	161.5	down grade	30.000	0.194	0.215	0.219
14	32	120	down grade	25.714	0.223	0.213	0.217
14	38	131.4	down grade	25.714	0.188	0.194	0.199
11	45	190	down grade	32.727	0.202	0.217	0.222
10	50	248.5	down grade	36.000	0.200	0.201	0.206

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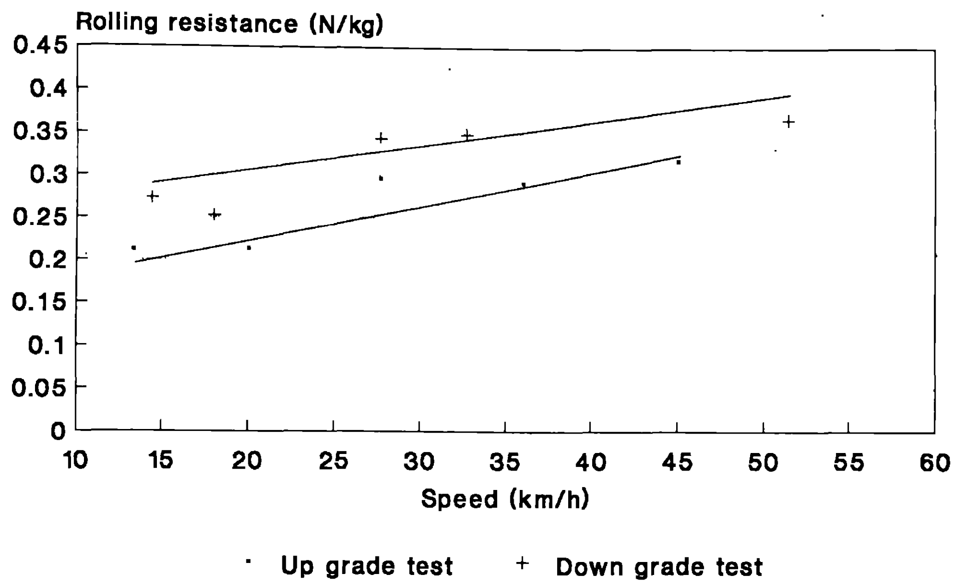
ROLLING RESISTANCE ASSESSMENT
Kleinkopje Colliery

ROAD	**Discard road**
SEGMENT	**700 - 750m**
GRADE	**0.002**
GRADE RESISTANCE	**0.016**
VEHICLE	**Toyota Hilux LWB**
VEHICLE MASS	**1266 kg**
TYRE & PRESSURE FRONT	**190 R14C, 190 kPa**
TYRE & PRESSURE REAR	**190 R14C, 190 kPa**
CONSTANT SPEED DISTANCE (m)	**100**

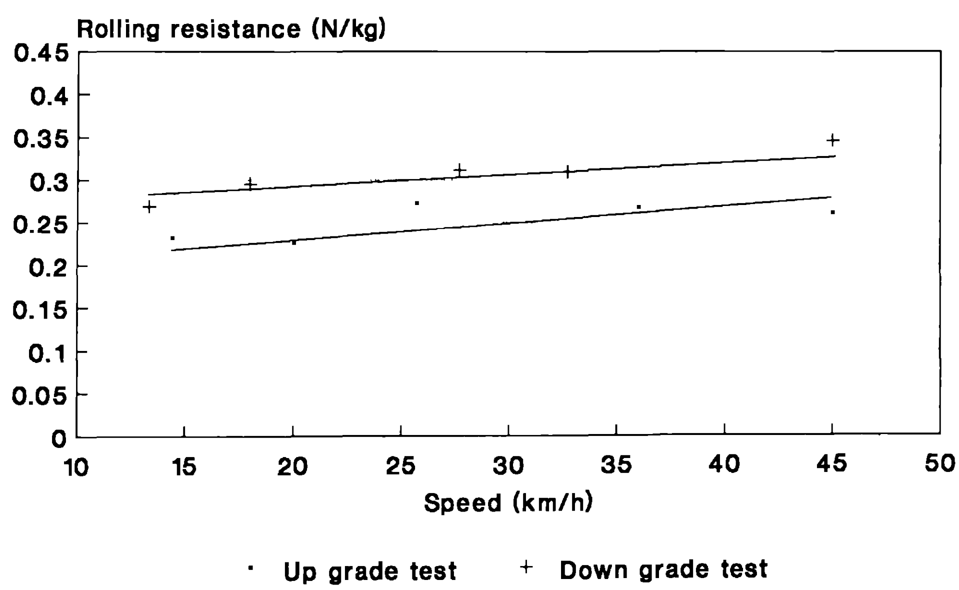
Constant speed t (s)	Deceleration t1 (s)	Deceleration d1 (m)	Direction	Constant speed (km/h)	Total resistance (N/kg) including grade: Using t1	Total resistance (N/kg) including grade: Using d1	Rolling resistance (N/kg)
24	16	31.8	up grade	15.000	0.260	0.273	0.257
19	19	48.3	up grade	18.947	0.277	0.287	0.270
14	24	87.4	up grade	25.714	0.298	0.292	0.276
10	31	167.0	up grade	36.000	0.323	0.299	0.283
8	38	249.0	up grade	45.000	0.329	0.314	0.297
25	17	32	down grade	14.400	0.235	0.250	0.266
19	20	53.2	down grade	18.947	0.263	0.260	0.277
13	28	110.6	down grade	27.692	0.275	0.268	0.284
10	33	171.1	down grade	36.000	0.303	0.292	0.309
8	36	240.6	down grade	45.000	0.347	0.325	0.341

ROLLING RESISTANCE TESTS
Kriel Colliery Main Haul Road



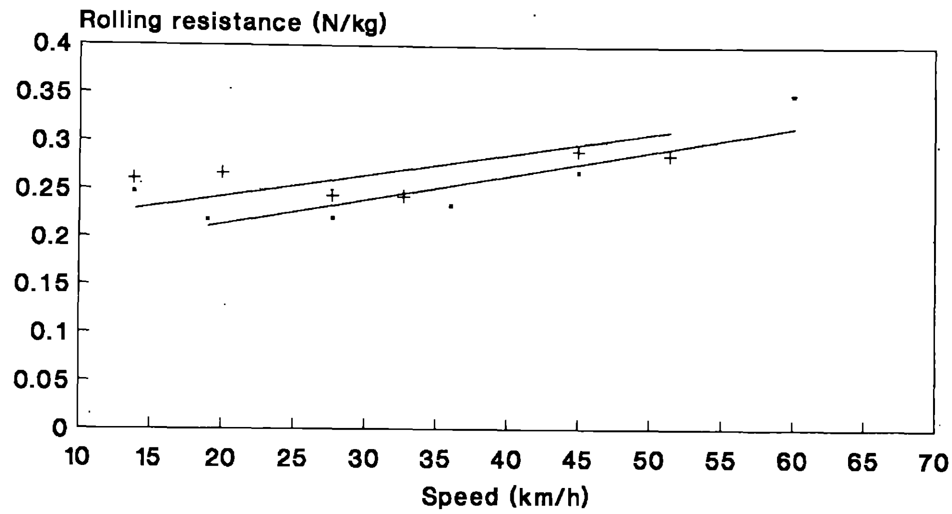
Using Toyota Hilux 2WD LWB
GVM 1266kg
190R14c tyres @ 190kPa inflation

ROLLING RESISTANCE TESTS
Kriel Colliery Ramp 7



Using Toyota Hilux 2WD LWB
GVM 1266kg
190R14c tyres @ 190kPa Inflation

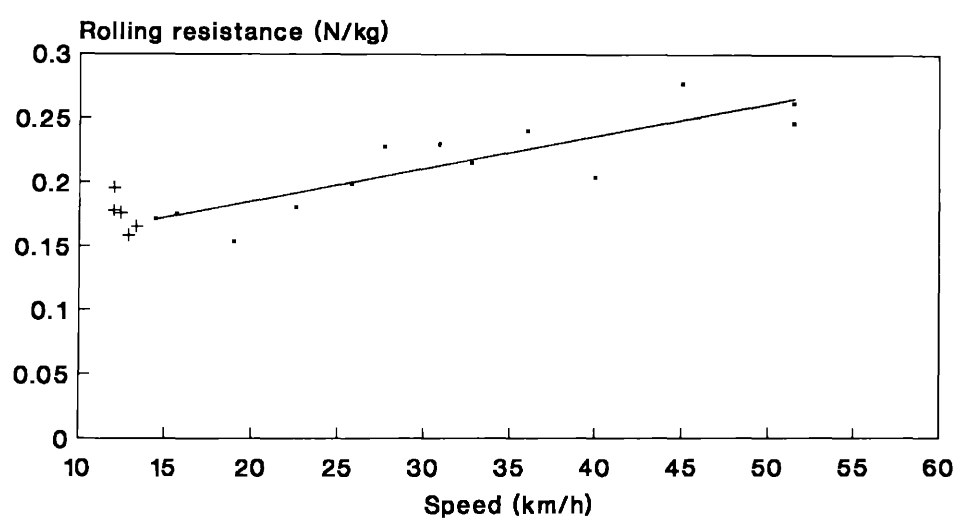
ROLLING RESISTANCE TESTS
Kromdraai Colliery Haul Road 2



· Up grade test + Down grade test

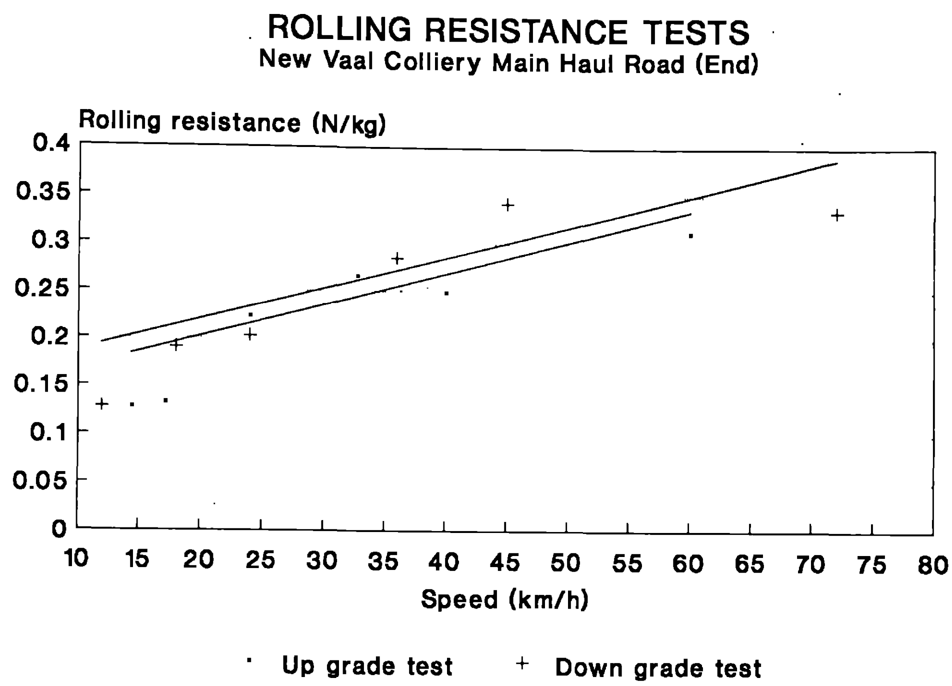
Using Toyota Hilux 2WD LWB
GVM 1266kg
190R14c tyres @ 190kPa Inflation

ROLLING RESISTANCE TESTS
Kromdraai Colliery Main Haul Road

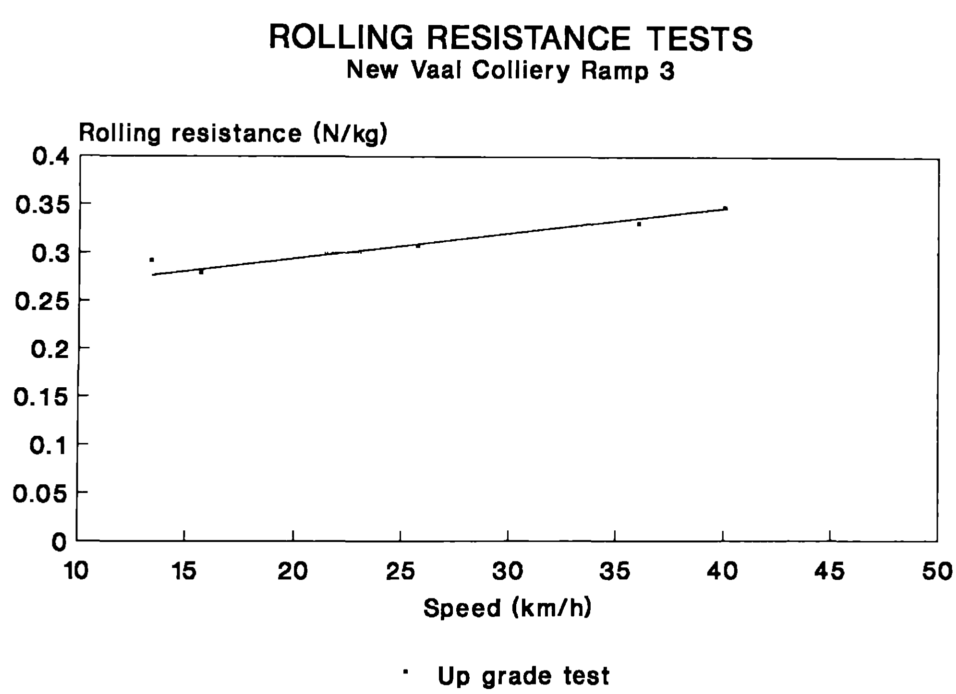


· Up grade test + Down grade test
(5 tests at approx. 12km/h)

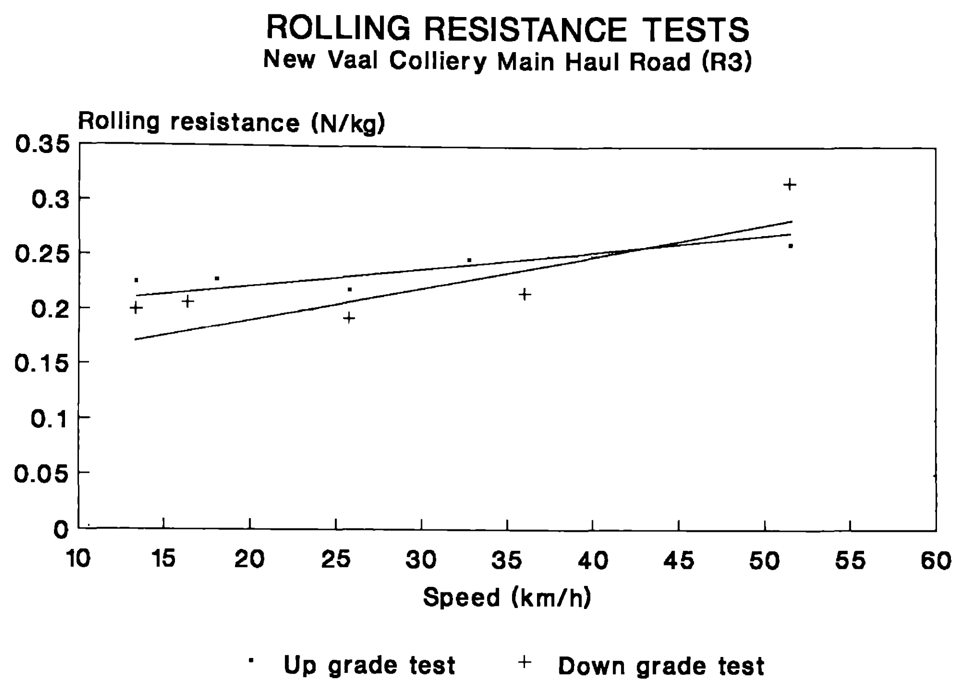
Using Toyota Hilux 2WD LWB
GVM 1266kg
190R14c tyres @ 190kPa inflation



Using Toyota Hilux 2WD LWB
GVM 1266kg
190R14c tyres @ 190kPa inflation

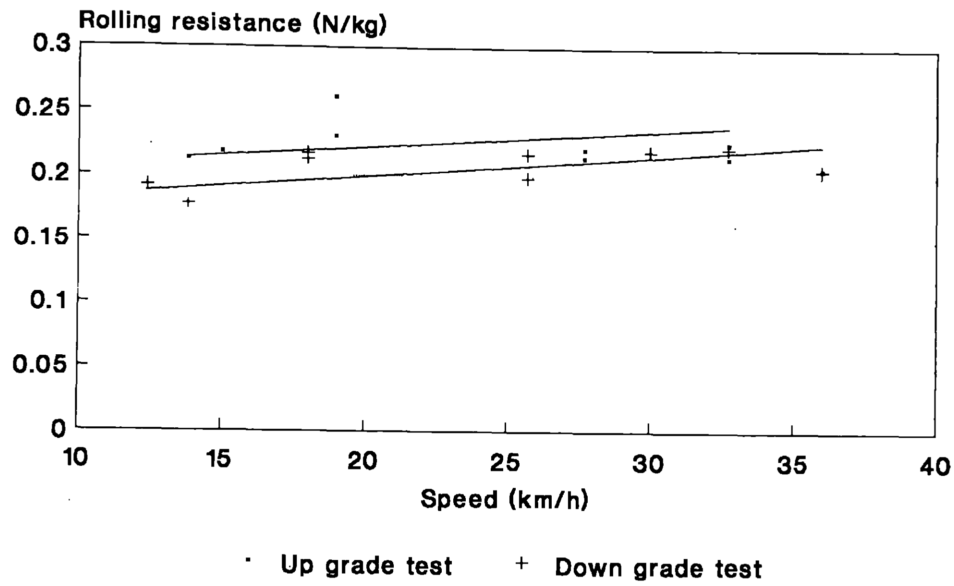


Using Toyota Hilux 2WD LWB
GVM 1266kg
190R14c tyres @ 190kPa inflation



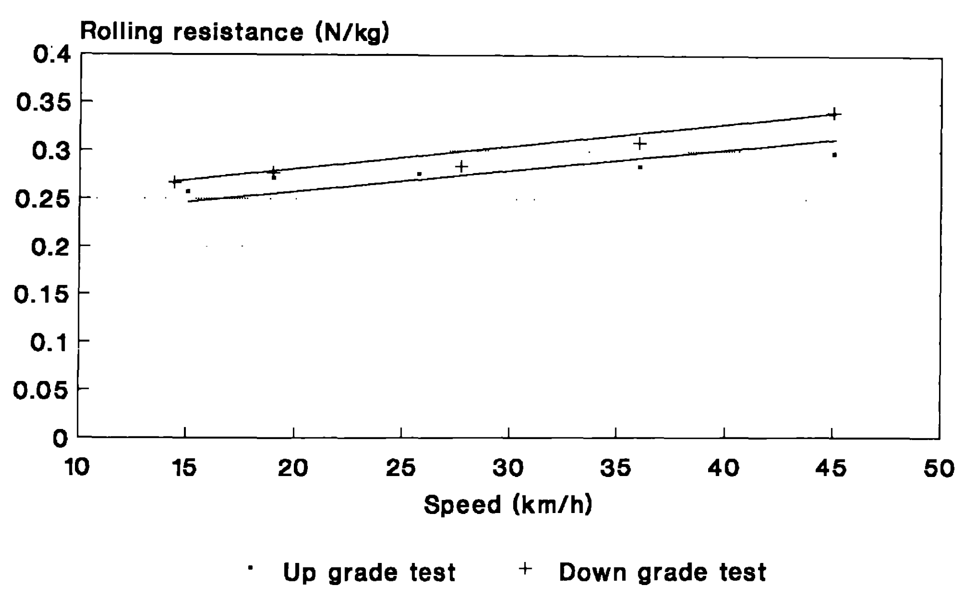
Using Toyota Hilux 2WD LWB
GVM 1266kg
190R14c tyres @ 190kPa inflation

ROLLING RESISTANCE TESTS
Kleinkopje Colliery 2A Haul Road



Using Toyota Hilux 2WD LWB
GVM 1266kg
190R14c tyres @ 190kPa inflation

ROLLING RESISTANCE TESTS
Kleinkopje Colliery Discards Road



Using Toyota Hilux 2WD LWB
GVM 1266kg
190R14c tyres @ 190kPa inflation

APPENDIX M

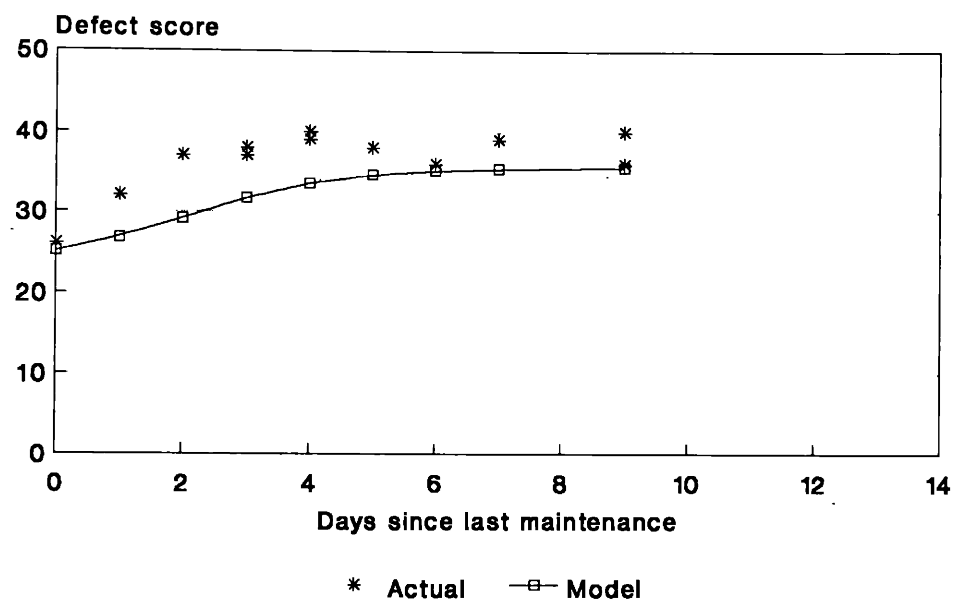
APPLIED ROAD ROUGHNESS DEFECT SCORE PROGRESSION MODELS

M-2

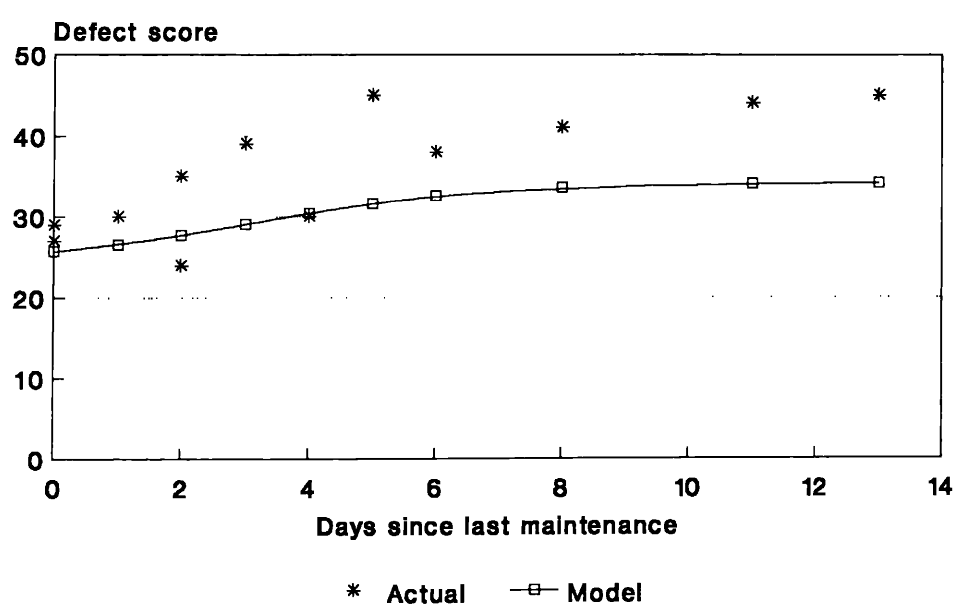
Contents

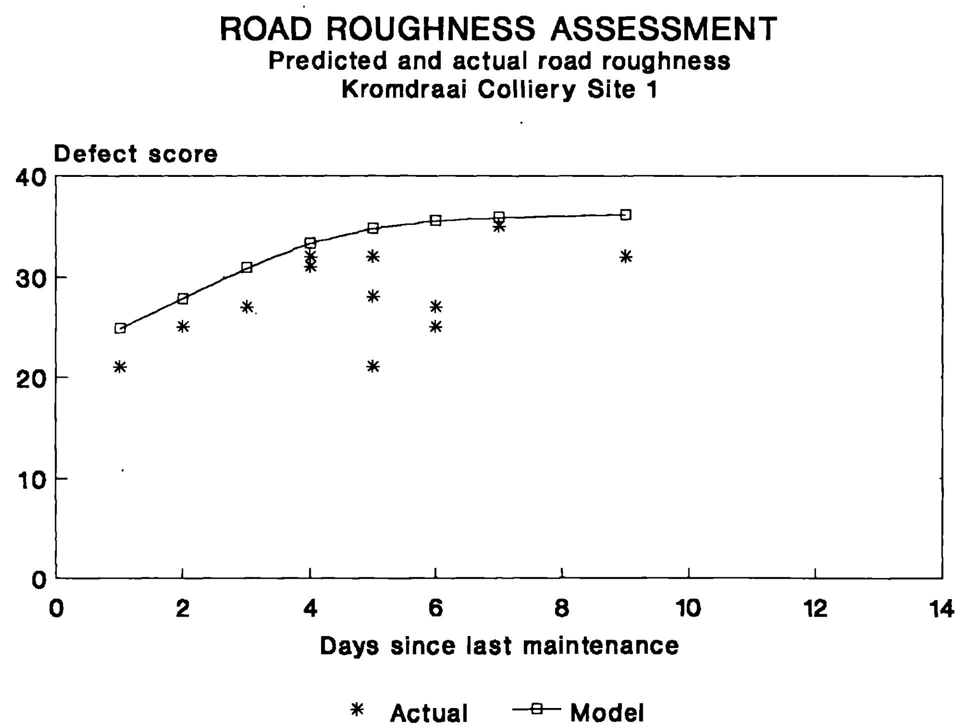
Comparison of individual mine site roughness progression (as measured during functional assessment) with roughness progression derived from model for mine sites comprising statistical data set;

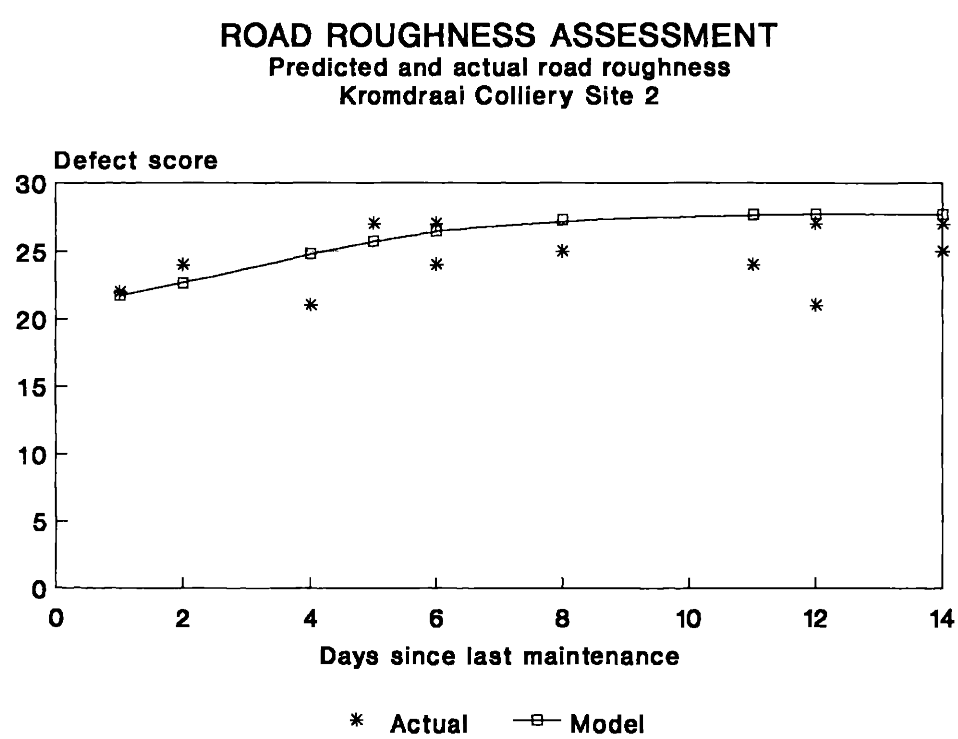
ROAD ROUGHNESS ASSESSMENT
Predicted and actual road roughness
Kriel Colliery Site 1



ROAD ROUGHNESS ASSESSMENT
Predicted and actual road roughness
Kriel Colliery Site 2

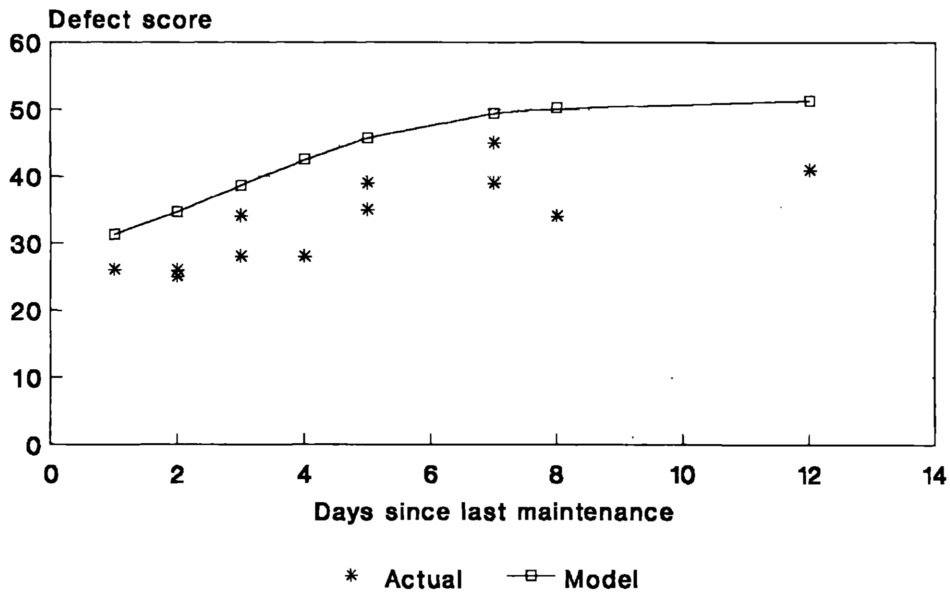



ROAD ROUGHNESS ASSESSMENT
Predicted and actual road roughness
Kromdraai Colliery Site 1
Defect score
40
30
20
10
0
0
2
4
6
8
10
12
14
Days since last maintenance
Actual
Model


ROAD ROUGHNESS ASSESSMENT
Predicted and actual road roughness
Kromdraai Colliery Site 2
Defect score
30
25
20
15
10
5
0
0
2
4
6
8
10
12
14
Days since last maintenance
Actual
Model

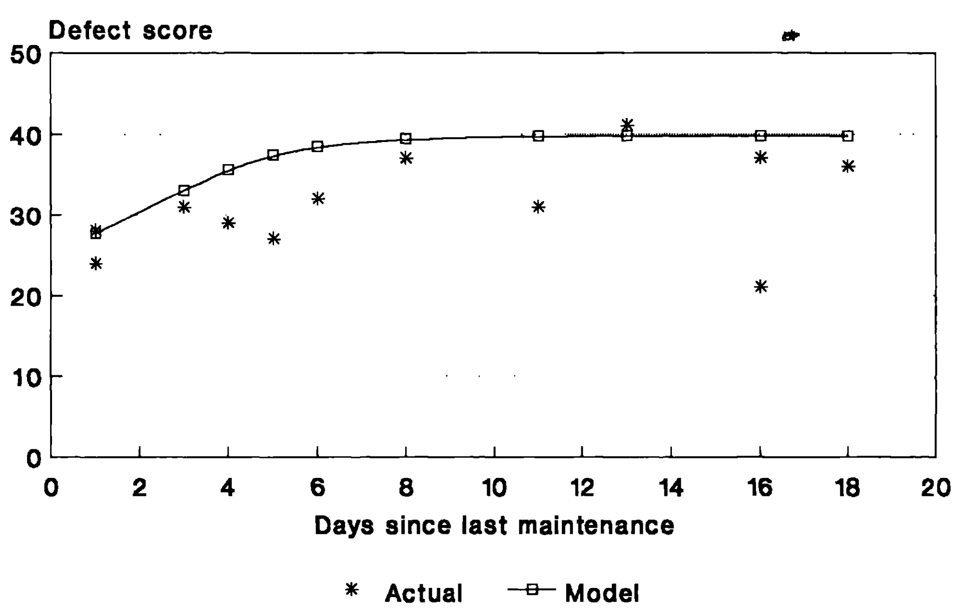
ROAD ROUGHNESS ASSESSMENT

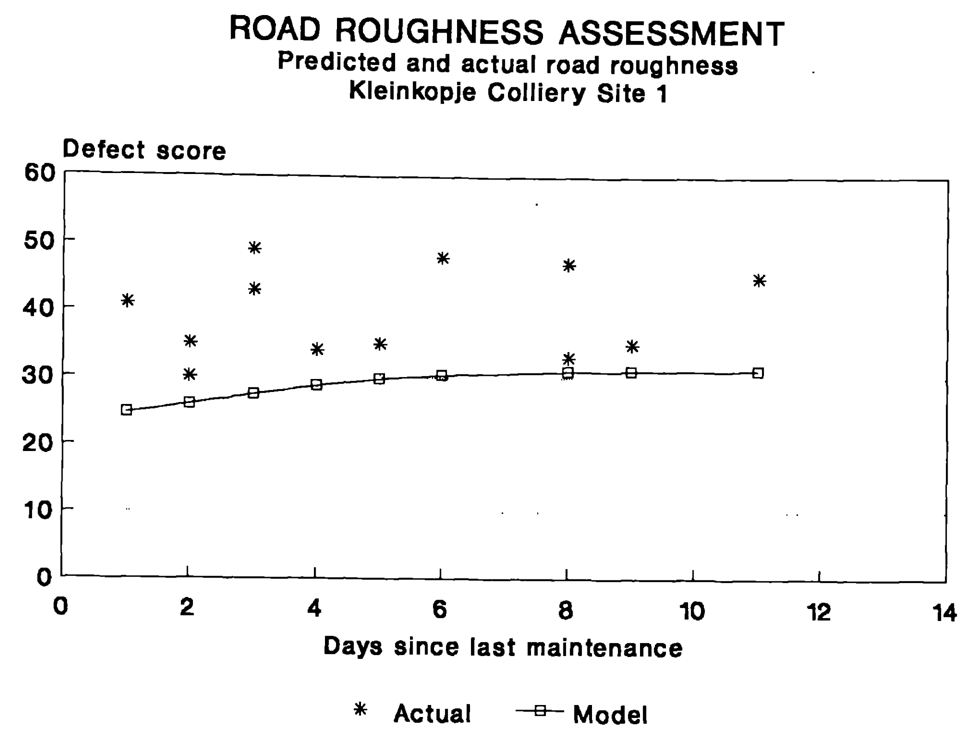
Predicted and actual road roughness
New Vaal Colliery Site 1

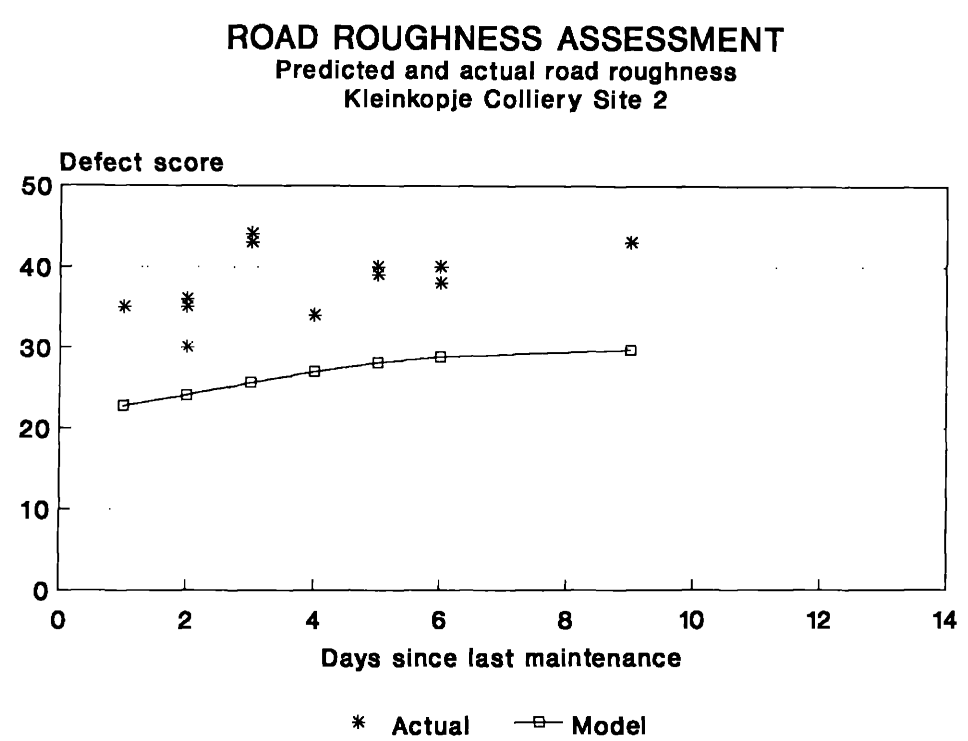


ROAD ROUGHNESS ASSESSMENT

Predicted and actual road roughness
New Vaal Colliery Site 2




ROAD ROUGHNESS ASSESSMENT
Predicted and actual road roughness
Kleinkopje Colliery Site 1
Defect score
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
Days since last maintenance
Actual
Model


ROAD ROUGHNESS ASSESSMENT
Predicted and actual road roughness
Kleinkopje Colliery Site 2
Defect score
50
40
30
20
10
0
0
2
4
6
8
10
12
14
Days since last maintenance
Actual
Model

APPENDIX N

SPECIFICATIONS OF VEHICLE SIMULATION FLEET FOR FUEL CONSUMPTION MODELLING

Caterpillar CAT 789

LOAD WEIGHT	VESSEL CAPACITY
154.2	105.00
(METRIC.T)	(CU.M 2:1)

TYPE	ENGINE	(ex. 100HP) POWER	COMMENT (Max. 18)	Mechanical drive, torque conv & DD lock-up
CAT789	CAT3516	1800HP	37.00-59	

	WHEELBASE	GRAVITY HEIGHT (mm)		GRAVITY RATIO *1	*1 A=a/L	
WEIGHT	(mm)	LOADED	EMPTY	LOADED	EMPTY	
119.800	5700	3780	2290	0.670	0.530	]

TR. WIDTH	DEF.&FINAL	TIRE RADIUS(m)		
(m) *2	RATIO	LOADED	EMPTY	
14.0	25.4600	1.460	1.550	]

** Oil Capacity of Components **

199.0	300.0	583.0	318.0	1439.0	] V(Liter)
250	1000	2000	2000	2000	] R(Hours)
(Engine)	(T/M)	(Final)	(Hydra.)	(Others)	

** Acceleration Factor **

RATIO	FORWARD	REVERSE	
5.048	0.433	0.100	]
3.476	0.602	0.367	]
2.222	0.752	0.536	]
1.529	0.833	0.658	]
1.000	0.885	0.746	]
0.689	0.909	0.787	]

** Travel Charactaristic Data **

SPEED (Km/H)	(TONS)	GEAR	
0.000	80.380	1	]
1.600	80.000	1	]
4.510	68.040	1	]
8.000	45.360	1	]
10.900	37.600	1	]
11.600	32.700	1	]
14.200	32.000	2	]
15.100	27.200	2	]
15.600	24.500	2	]
18.300	22.700	3	]
20.800	19.500	3	]
21.200	18.100	3	]
24.100	16.500	4	]
27.700	14.700	4	]
28.200	13.400	4	]
29.900	13.300	5	]
36.900	11.400	5	]
38.500	10.000	5	]
40.200	9.900	6	]
50.400	8.200	6	]
55.000	5.100	6	]
55.100	0.000	6	]

** Retarder Data **

Rtw *5 (TONNES)	SPEED LIMIT (Km/H) DISTANCE	DISTANCE	DISTANCE	DISTANCE	*5 Rtw=WEIGHT
0.0	55.0	55.0	55.0	55.0	]
11.1	55.0	55.0	55.0	55.0	]
12.0	55.0	55.0	55.0	41.7	]
14.2	55.0	55.0	55.0	41.7	]
15.0	55.0	55.0	55.0	30.0	]
17.3	55.0	55.0	55.0	30.0	]
19.2	55.0	55.0	41.7	30.0	]
21.0	55.0	55.0	30.0	22.5	]
23.1	41.7	41.7	30.0	22.5	]
24.0	41.7	41.7	30.0	16.7	]
24.3	30.0	30.0	30.0	16.7	]
29.3	30.0	30.0	22.5	16.7	]
30.0	22.5	22.5	22.5	16.7	]
35.2	22.5	22.5	16.7	16.7	]
38.1	16.7	16.7	16.7	12.8	]
40.1	16.7	16.7	16.7	12.8	]
45.2	16.7	16.7	12.8	12.8	]
46.2	12.8	12.8	12.8	12.8	]
51.0	12.8	12.8	12.8	9.0	]

** Fuel Consumption **

ROTATION (RPM)	FUEL CM. (GR/PSh)	POWER (PS)	
800	300.0	398.0	]
1000	200.0	684.0	]
1200	200.0	1039.0	]
1400	164.0	1349.0	]
1600	161.0	1537.0	]
1800	162.0	1663.0	]
2000	165.0	1636.0	]
2200	175.0	800.0	]
2300	200.0	192.0	]
2360	700.0	0.0	]

Caterpillar CAT 785

LOAD WEIGHT	VESSEL CAPACITY
117.9	78.00
(METRIC.T)	(CU.M 2:1)

TYPE	ENGINE	POWER (ex. 100HP)	COMMENT (Max. 18) Mechanical drive, torque conv & DD lock-up
CAT785	CAT3512	1380HP	33.00-51

WEIGHT	WHEELBASE (mm)	GRAVITY HEIGHT (mm) LOADED	EMPTY	GRAVITY RATIO *1 LOADED	EMPTY	*1 A=a/L
94.900	5180	3375	2120	0.670	0.520	]

TR. WIDTH (m) *2	DEF.&FINAL RATIO	TIRE RADIUS(m) LOADED	EMPTY	
12.0	22.1000	1.395	1.475	]

** Oil Capacity of Components **

(Engine)	(T/M)	(Final)	(Hydra.)	(Others)	
132.0	339.0	628.0	977.0	339.0	] V(Liter)
250	1000	2000	2000	2000	] R(Hours)

** Acceleration Factor **

RATIO	LOADED	EMPTY	
5.048	0.433	0.100	]
3.475	0.602	0.367	]
2.222	0.752	0.536	]
1.529	0.833	0.658	]
1.000	0.885	0.746	]
0.689	0.909	0.787	]

** Travel Charactaristic Data **

SPEED (Km/H)	(TONS)	GEAR	
0.000	78.300	1	]
2.000	68.000	1	]
5.000	50.000	1	]
7.700	35.400	1	]
7.800	35.000	1	]
10.000	30.800	1	]
11.200	25.000	1	]
11.300	24.800	2	]
14.600	21.000	2	]
15.400	18.600	2	]
15.500	18.500	3	]
20.000	15.000	3	]
20.400	13.800	3	]
20.500	13.600	4	]
26.900	11.340	4	]
27.700	10.100	4	]
27.800	10.000	5	]
36.900	8.100	5	]
37.700	7.500	5	]
37.800	7.400	6	]
40.800	7.300	6	]
50.000	6.200	6	]
53.800	3.630	6	]
54.000	0.000	6	]

** Retarder Data **

Rtw *5 (TONNES)	SPEED LIMIT (Km/H) DISTANCE	DISTANCE	DISTANCE	DISTANCE	
0.0	58.0	58.0	58.0	58.0	]
5.0	58.0	58.0	58.0	58.0	]
7.0	58.0	58.0	58.0	58.0	]
12.7	58.0	58.0	58.0	43.0	]
16.6	58.0	58.0	43.0	31.6	]
16.9	43.0	43.0	31.6	31.6	]
18.9	43.0	43.0	31.6	23.3	]
22.4	31.6	31.6	23.3	23.3	]
27.8	23.3	23.3	17.2	17.2	]
29.6	17.2	17.2	17.2	17.2	]
33.6	17.2	17.2	12.7	12.7	]
40.0	12.7	12.7	12.7	12.7	]
40.5	12.7	12.7	12.7	11.0	]
41.8	12.7	12.7	11.0	5.0	]

*5 Rtw=WEIGHT

** Fuel Consumption **

ROTATION (RPM)	FUEL CM. (GR/PSh)	POWER (PS)	
800	193.0	472.0	]
100	177.5	705.0	]
1200	167.0	925.0	]
1400	158.0	1175.0	]
1600	155.0	1334.0	]
1800	154.3	1350.0	]
2000	157.5	1312.0	]
2050	159.0	1200.0	]

Euclid R170

LOAD WEIGHT (METRIC.T)	VESSEL CAPACITY (CU.M 2:1)
154.2	105.00

TYPE	ENGINE	POWER	COMMENT (Max. 18) Torque conv & DD lock-up to electric WM
R170	Cummins KTA50C	1800HP	37.00-59

WEIGHT	WHEELBASE (mm)	GRAVITY HEIGHT (mm) LOADED	EMPTY	GRAVITY RATIO *1 LOADED	EMPTY
119.800	5700	3780	2290	0.670	0.530]

*1 A=a/L

TR. WIDTH (m) *2	DEF.&FINAL RATIO	TIRE RADIUS(m) LOADED	EMPTY
14.0	25.4600	1.460	1.550]

** Oil Capacity of Components **

(Engine)	(T/M)	(Final)	(Hydra.)	(Others)	
199.0	300.0	583.0	318.0	1439.0	] V(Liter)
250	1000	2000	2000	2000	] R(Hours)

** Acceleration Factor **

RATIO	FORWARD	REVERSE
5.048	0.433	0.100]
3.476	0.602	0.367]
2.222	0.752	0.536]
1.529	0.833	0.658]
1.000	0.885	0.746]
0.689	0.909	0.787]

** Travel Charactaristic Data **

SPEED (Km/H)	(TONS)	GEAR
0.000	80.380	1]
1.600	80.000	1]
4.510	68.040	1]
8.000	45.360	1]
10.900	37.600	1]
11.600	32.700	1]
14.200	32.000	2]
15.100	27.200	2]
15.600	24.500	2]
18.300	22.700	3]
20.800	19.500	3]
21.200	18.100	3]
24.100	16.500	4]
27.700	14.700	4]
28.200	13.400	4]
29.900	13.300	5]
36.900	11.400	5]
38.500	10.000	5]
40.200	9.900	6]
50.400	8.200	6]
55.000	5.100	6]
55.100	0.000	6]

** Retarder Data **

Rtw *5 (TONNES)	SPEED LIMIT (Km/H) DISTANCE	DISTANCE	DISTANCE	*5 Rtw=WEIGHT DISTANCE	
0.0	55.0	55.0	55.0	55.0	]
11.1	55.0	55.0	55.0	55.0	]
12.0	55.0	55.0	55.0	41.7	]
14.2	55.0	55.0	55.0	41.7	]
15.0	55.0	55.0	55.0	30.0	]
17.3	55.0	55.0	55.0	30.0	]
19.2	55.0	55.0	41.7	30.0	]
21.0	55.0	55.0	30.0	22.5	]
23.1	41.7	41.7	30.0	22.5	]
24.0	41.7	41.7	30.0	16.7	]
24.3	30.0	30.0	30.0	16.7	]
29.3	30.0	30.0	22.5	16.7	]
30.0	22.5	22.5	22.5	16.7	]
35.2	22.5	22.5	16.7	16.7	]
38.1	16.7	16.7	16.7	12.8	]
40.1	16.7	16.7	16.7	12.8	]
45.2	16.7	16.7	12.8	12.8	]
46.2	12.8	12.8	12.8	12.8	]
51.0	12.8	12.8	12.8	9.0	]

** Fuel Consumption **

ROTATION (RPM)	FUEL CM. (GR/PSh)	POWER (PS)	
800	300.0	398.0	]
1000	200.0	684.0	]
1200	200.0	1039.0	]
1400	164.0	1349.0	]
1600	161.0	1537.0	]
1800	162.0	1663.0	]
2000	165.0	1636.0	]
2200	175.0	800.0	]
2300	200.0	192.0	]
2360	700.0	0.0	]

Dresser-Haulpak 630EH

LOAD WEIGHT	VESSEL CAPACITY
163.0	103.00
(METRIC.T)	(CU.M 2:1)

TYPE	ENGINE	POWER	COMMENT (Max. 18) Torque conv & DD lock-up to electric WM
HPK630E	Detroit 16v 14977B	1800HP	36.00-51

WHEELBASE GRAVITY HEIGHT (mm) GRAVITY RATIO *1 *1 A=a/L

WEIGHT	(mm)	LOADED	EMPTY	LOADED	EMPTY	
114.100	5440	3780	2290	0.667	0.508	]

TR. WIDTH DEF.&FINAL TIRE RADIUS(m)

(m) *2	RATIO	LOADED	EMPTY	
14.0	24.8100	1.460	1.550	]

** Oil Capacity of Components **

214.0	1.0	34.0	496.0	314.0	] V(Liter)
250	1000	2000	2000	2000	] R(Hours)
(Engine)	(T/M)	(Final)	(Hydra.)	(Others)	

** Acceleration Factor **

RATIO	LOADED	EMPTY	
5.650	0.682	0.467	]
4.290	0.786	0.599	]
3.180	0.862	0.718	]
2.500	0.910	0.805	]
1.850	0.939	0.862	]
1.350	0.960	0.907	]
1.000	0.959	0.905	]

** Travel Charactaristic Data **

SPEED (Km/H)	(TONS)	GEAR	
0.100	68.000	1	]
4.000	68.000	1	]
7.300	45.400	1	]
8.050	40.800	1	]
9.660	36.300	1	]
11.270	31.800	2	]
13.690	27.200	3	]
16.910	22.680	4	]
21.410	18.140	5	]
28.820	13.610	6	]
35.100	11.340	7	]
39.450	9.070	7	]
45.890	6.800	7	]
52.300	5.260	7	]
52.300	4.000	7	]
52.300	3.000	7	]
52.300	2.000	7	]
52.300	1.000	7	]
52.300	0.000	7	]
52.300	0.000	7	]

** Retarder Data **

*5 Rtw=WEIGHT

Rtw *5 (TONNES)	SPEED LIMIT (Km/H) 300M -	300-450M	450-700M	700M -	
0.0	52.3	52.3	52.3	52.3	]
5.0	52.3	52.3	52.3	52.3	]
9.0	52.3	52.3	52.3	52.3	]
11.3	47.5	47.5	47.5	47.5	]
13.6	43.5	43.5	43.5	43.5	]
15.9	41.1	41.1	41.1	41.1	]
18.1	38.2	38.2	38.2	38.2	]
22.7	33.5	33.5	33.5	33.5	]
27.2	28.2	28.2	28.2	28.2	]
31.8	24.0	24.0	24.0	24.0	]
35.8	20.9	20.9	20.9	20.9	]
35.8	15.0	15.0	15.0	15.0	]
36.0	8.5	8.5	8.5	8.5	]
36.0	0.1	0.1	0.1	0.1	]

** Fuel Consumption **

ROTATION (RPM)	FUEL CM. (GR/PSh)	POWER (PS)	
800	305.0	398.0	]
1000	205.0	684.0	]
1200	205.0	1039.0	]
1400	170.0	1349.0	]
1600	163.0	1535.0	]
1800	165.0	1660.0	]
2000	167.0	1636.0	]
2200	178.0	882.0	]
2300	200.0	193.0	]
2360	700.0	0.0	]

Caterpillar CAT 793

LOAD WEIGHT	VESSEL CAPACITY
218.0	129.40
(METRIC.T)	(CU.M 2:1)

TYPE	ENGINE	POWER	COMMENT (Max. 18) Mechanical drive, torque conv & DD lock-up
CAT793	CAT3516	2160HP	40.00-57

WEIGHT	WHEELBASE (mm)	GRAVITY HEIGHT (mm) LOADED	EMPTY	GRAVITY RATIO *1 LOADED	EMPTY	*1 A=a/L
143.900	5900	4330	2630	0.664	0.531	]

TR. WIDTH (m) *2	DEF.&FINAL RATIO	TIRE RADIUS(m) LOADED	EMPTY	
20.0	26.8000	1.490	1.570	]

** Oil Capacity of Components **

199.0	300.0	662.0	189.0	1136.0	] V(Liter)
250	1000	2000	2000	200	] R(Hours)
(Engine)	(T/M)	(Final)	(Hydra.)	(Others)	

** Acceleration Factor **

RATIO	LOADED	EMPTY	
5.048	0.433	0.100	]
3.476	0.602	0.367	]
2.222	0.752	0.536	]
1.529	0.833	0.658	]
1.000	0.885	0.746	]
0.689	0.909	0.787	]

** Travel Charactaristic Data **

SPEED (Km/H)	(TONS)	GEAR	
0.000	98.700	1	]
2.500	90.700	1	]
8.200	55.000	1	]
11.500	40.000	1	]
12.000	39.000	2	]
14.000	35.000	2	]
15.500	30.000	2	]
16.000	29.500	3	]
20.500	25.000	3	]
21.000	22.200	4	]
27.000	18.100	4	]
28.500	15.600	4	]
36.000	13.700	5	]
37.500	12.000	5	]
43.500	11.340	6	]
50.000	9.500	6	]
53.600	6.200	6	]
53.600	0.000	6	]

** Retarder Data **

Rtw *5	SPEED LIMIT (Km/H)				*5 Rtw=WEIGHT
(TONNES)	DISTANCE	DISTANCE	DISTANCE	DISTANCE	
0.0	54.0	54.0	54.0	54.0	]
12.9	54.0	54.0	54.0	54.0	]
14.0	54.0	54.0	54.0	40.5	]
20.7	54.0	54.0	54.0	40.5	]
25.0	54.0	54.0	40.5	29.5	]
27.6	40.5	40.5	40.5	29.5	]
31.0	40.5	40.5	29.5	22.0	]
32.0	29.5	29.5	29.5	22.0	]
33.6	29.5	29.5	29.5	22.0	]
36.2	29.5	29.5	22.0	22.0	]
38.8	29.5	29.5	22.0	16.4	]
40.0	22.0	22.0	22.0	16.4	]
41.4	22.0	22.0	22.0	16.4	]
42.0	22.0	22.0	16.4	16.4	]
47.4	22.0	22.0	16.4	16.4	]
48.0	16.4	16.4	16.4	16.4	]
50.0	16.4	16.4	16.4	16.4	]
60.3	16.4	16.4	12.0	12.0	]
61.0	12.0	12.0	12.0	12.0	]
64.7	12.0	12.0	9.0	9.0	]

** Fuel Consumption **

ROTATION	FUEL CM.	POWER	
(RPM)	(GR/PSh)	(PS)	
800	360.0	478.0	]
1000	240.0	821.0	]
1200	240.0	1247.0	]
1400	197.0	1620.0	]
1600	193.0	1844.0	]
1800	195.0	1996.0	]
2000	198.0	1963.0	]
2200	210.0	960.0	]
2300	240.0	230.0	]
2360	840.0	0.0	]

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APPENDIX O

MINE HAUL ROAD GEOEMETRY AND PRODUCTION STATISTICS

KRIEL COLLIERY ROAD GEOMETRY AND COAL PRODUCTION STATISTICS SUMMARY						
Haul road section	**ROM tons (pa)**	**Length of section (m)**	**Rise (+) or fall (-) of section (m)**	**Grade (%)**	**Curvature of section (°)**	**Curvature (°/km)**
MAIN	4703000	4660	70.2	1.51	134	28.76
R6	1061000	1920	17.4	0.91	82	42.71
R7	2482000	2190	31.3	1.43	56	25.57
R8/11	1160000	3785	36.3	0.96	141	37.25

KROMDRAAI COLLIERY ROAD GEOMETRY AND COAL PRODUCTION STATISTICS SUMMARY						
Haul road section	**ROM tons (pa) 4200265**	**Length of section (m)**	**Rise (+) or fall (-) of section (m)**	**Grade (%)**	**Curvature of section (°)**	**Curvature (°/km)**
RAMP-TIP		195	11	5.64	0	0.00
MAIN	4200265	943	-16	-1.70	0	0.00
HR1	3520159	3240	32	0.99	296	91.36
HR2	680106	4530	25	0.55	97	21.41

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NEW VAAL COLLIERY ROAD GEOMETRY AND COAL PRODUCTION STATISTICS SUMMARY						
Haul road section	**ROM tons (pa)**	**Length of section (m)**	**Rise (+) or fall (-) of section (m)**	**Grade (%)**	**Curvature of section (°)**	**Curvature (°/km)**
RAMP-TIP	14451000	36	6	16.67	16	444.44
MAIN	14451000	540	0.6	0.11	35	64.81
R0-R2	9200000	1580	2.8	0.18	32	20.25
R2-R3	6685000	1010	5.1	0.50	0	0.00
R3-R4	4497000	698	2.7	0.39	0	0.00
R4-R6/7	3950000	800	-7.4	-0.93	16	20.00
R6/7-R9	1420000	581	0.6	0.10	0	0.00
R0	5299000	650	19	2.92	56	86.15
R2	2515000	490	17	3.47	0	0.00
R3	2187000	830	21	2.53	0	0.00
R4	547000	640	28	4.38	76	118.75
R6/7	2530000	820	24	2.93	24	29.27
R9	1420000	510	27	5.29	184	360.78

KLEINKOPJE COLLIERY

ROAD GEOMETRY AND COAL PRODUCTION STATISTICS SUMMARY

Haul road section	ROM tons (pa)	Length of section (m)	Rise (+) or fall (-) of section (m)	Grade (%)	Curvature of section (°)	Curvature (°/km)
MAIN-TIP	5241000	498	1	0.20	0	0.00
5W-MAIN	1882000	2217	40	1.80	80	36.08
R13/14-MAIN	2173000	2457	41	1.67	34	13.84
2A9-MAIN	1186000	1503	41	2.73	74	49.23
2A8-MAIN	395000	896	11	1.23	0	0.00
2A7-MAIN	395000	440	0	0.00	0	0.00
3A-TIP	2743000	2276	4	0.18	21	9.23
R15	627000	753	17	2.26	12	15.94
R16	627000	918	19	2.07	28	30.50
R17	628000	1435	23	1.60	64	44.60
R7	395000	355	6.1	1.72	0	0.00
R8	395000	386	8.8	2.28	0	0.00
R9	396000	522	10.2	1.95	0	0.00

APPENDIX P

LISTING OF HAUL ROAD MMS MODEL COMPUTER PROGRAM AND ASSESSMENT DATA

```
REM     Program HAULOPT
REM     To investigate optimum maintenance frequency for lowest overall
REM     vehicle operating and road maintenance total cost.
REM     By R J Thompson March 1996
REM     Version 1 of March 1996

COMMON SHARED segdata(), segname$(), segm!, mfleet(), voccostmod(), minename$
DECLARE SUB optimalsol ()
DECLARE SUB tot ()
DECLARE SUB maintcost ()
DECLARE SUB totalvoccost ()
DECLARE SUB othercost ()
DECLARE SUB speed ()
DECLARE SUB costmodeledit ()
DECLARE SUB datain ()
DECLARE SUB titles ()
DECLARE SUB costmodels ()


'************************ERROR HANDLER*************************************
xox:
SCREEN 9: COLOR 15
ON ERROR GOTO ERRORHANDLER
KEY 1, " Quit"
ON KEY(1) GOSUB ENDPROG
KEY(1) ON
KEY 3, ""
KEY(3) OFF
KEY 7, ""
KEY(7) OFF
KEY ON

'**************************Read initial data and titles**********************
CALL titles
CALL datain

'*****************Edit cost model equations and read var data****************

CALL costmodels

'***********************Calculate speeds, fuel and fuel cost*****************

' Based on total cost per segment according to length, tonnage
' and vehicle passes per day

CALL speed

'***********************Calculate tyre, parts and labour costs***************

' Based on total cost per segment according to length, tonnage
' and vehicle passes per day

CALL othercost
```

```
'**************************Calculate total VOC per section*******************

'Add individual segment costs to get total segment VOC variation with
'days since last maintenance

CALL totalvoccost

'***********************Calc total maintenance cost per section**************

'Calculate total road maintenance costs and productivity
'for each section over maintenance interval.

CALL maintcost

'******************************Calc total costs******************************

'Calculate total cost for each segment and the complete haul

CALL tot

'***********************Calc optimal maintenance policy**********************

CALL optimalsol

LOCATE 23, 54: COLOR 14, 1: PRINT ; "Press any key to exit"
a$ = INPUT$(1)

END

'****************************** ERROR HANDLER ********************************
ERRORHANDLER:
CLS : SCREEN 9
LINE (40, 100)-(600, 200), 13, B
LOCATE 9, 25: COLOR 14: PRINT "Error"; ERR; "has occurred.": COLOR 15
SELECT CASE ERR
CASE 11
  LOCATE 10, 25: PRINT "You have divided by zero - rerun program with new values"
  LOCATE 12, 25: COLOR 13: PRINT "Hit any key to continue"
  a$ = INPUT$(1)
  END
CASE 4
  LOCATE 10, 25: PRINT "Out of data - rerun program with new data"
  LOCATE 12, 25: COLOR 13: PRINT "Hit any key to continue"
  a$ = INPUT$(1)
  END
CASE 6, 7
  LOCATE 10, 25: PRINT "Overflow or out of memory - reduce segments"
  LOCATE 12, 25: COLOR 13: PRINT "Hit any key to continue"
  a$ = INPUT$(1)
  END
CASE 9
  LOCATE 10, 25: PRINT "Subscript out of range - rerun program with new values"
  LOCATE 12, 25: COLOR 13: PRINT "Hit any key to continue"
  a$ = INPUT$(1)
  END
```

```
CASE 13
  LOCATE 10, 25: PRINT "Type mismatch - rerun program with new values"
  LOCATE 12, 25: COLOR 13: PRINT "Hit any key to continue"
  a$ = INPUT$(1)
  END
CASE 40
  LOCATE 10, 25: PRINT "Variable required - rerun program with new values"
  LOCATE 12, 25: COLOR 13: PRINT "Hit any key to continue"
  a$ = INPUT$(1)
  END
CASE 51
  LOCATE 10, 25: PRINT "Internal error"
  LOCATE 12, 25: COLOR 13: PRINT "Press any key to rerun"
  WHILE INKEY$ = "": WEND
  RESUME
CASE 69
  LOCATE 10, 25: PRINT "Buffer overflow - please rerun program"
  LOCATE 11, 25: PRINT "Redo from start"
  LOCATE 13, 25: COLOR 13: PRINT "Hit any key to continue"
  a$ = INPUT$(1)
  RESUME XOX
CASE ELSE
RESUME
END SELECT

ENDPROG:
CLS
END


SUB titles

BEGIN:
SCREEN 0, 0, 0, 0: COLOR 2, 9: CLS                    'set screen
PRINT : PRINT : PRINT , "Program HAULOPT by R J Thompson, 1996": COLOR 7, 1
PRINT : PRINT : PRINT , "To investigate optimum maintenance frequency for a"
PRINT , "mine haul road in which road user costs are minimised."
PRINT : PRINT , "Road user costs include vehicle operating cost components"
PRINT , "of fuel, tyres, parts and labour and the cost of maintaining the"
PRINT , "road using water car and grader."
PRINT : PRINT , "A mine haul-road network is required which is split into"
PRINT , "individual segments depending on tonnage and wearing course"
PRINT , "material properties of each segment."
PRINT :  PRINT , "The program accomodates 2-axle rear-dump haul trucks of "
PRINT , "120-220t capacity, electric or mechanical drive."
COLOR 14, 1: LOCATE 22, 54: PRINT "Press any key to continue": a$ = INPUT$(1)
CLS : COLOR 15, 1

END SUB
```

```
SUB datain

intro1:
CLS : COLOR 2, 9
PRINT , "HAUL ROAD GEOMETRY AND MATERIAL PROPERTY DATA"
COLOR 7, 1: PRINT : INPUT "          Enter name of mine"; minename$
INPUT "            Enter number of road segments "; segm!

tryagain1:
COLOR 14, 1: LOCATE 23, 14: PRINT , "If data is correct press C else E to edit."
a$ = INPUT$(1)
IF a$ <> "E" AND a$ <> "e" AND a$ <> "c" AND a$ <> "C" THEN GOTO tryagain1
IF a$ = "E" OR a$ = "e" THEN GOTO intro1
IF a$ = "c" OR a$ = "C" THEN LOCATE 23, 1: COLOR 1, 1: PRINT "
      "
CLS : COLOR 7, 1

'************************Dimension data arrays*******************************

DIM segname$(segm!)          'name of segment array
DIM segdata(28, segm!, 21)   '1=section length
                             '2=width of road
                             '3=grade percent
                             '4=vehicle gvm
                             '5=vehicle uvm
                             '6=drive type 1-elec, 0-mech
                             '7=repalcement price VP
                             '8=daily tonnage kt
                             '9= material, 1-mix, 0-ferricrete
                             '10=CBR
                             '11=SP
                             '12=GC
                             '13=DR
                             '14=PI
                             '15=rds
                             '16=RR%
                             '17=average vehicle estimated speed
                             '18=TR% laden dir
                             '19=TR% unladen dir
                             '20=laden speed
                             '21=unladen speed
                             '22=total fuel cost
                             '23=total tyre cost
                             '24=total parts cost
                             '25=total labour
                             '26=vehicle age '000hrs
                             '27=total VOC
                             '28=total road maintenance


DIM mfleet(6)                '1=number of graders
                             '2=grader hours per day
                             '3=number of water-cars
                             '4=water-car hours per day
                             '5=grader operating cost
                             '6=water-car operating cost
```

```
DIM voccostmod(11)
                                    '1=const tyre
                                    '2=coeff IRI
                                    '3=coeff GR
                                    '4=const parts
                                    '5=coeff p/vp
                                    '6=coeff H^
                                    '7=coeff labour v/vp
                                    '8=coeff v/vp^
                                    '9=price escalation
                                    '10=diesel fuel price
                                    '11=tyre price

segcount! = 1
introa:
CLS : COLOR 2, 1: PRINT , "HAUL TRUCK DATA"
COLOR 7, 1: PRINT : PRINT , "This data is common to all"; segm!; " segments specified"
PRINT :
    INPUT "Vehicle GVM (t)                    ", segdata(4, segcount!, 1)
    INPUT "Vehicle UVM (t)                    ", segdata(5, segcount!, 1)
    INPUT "Vehicle drive type, 1-elec, 0-mech  ", segdata(6, segcount!, 1)
    INPUT "Vehicle replacement price (Rm)      ", segdata(7, segcount!, 1)
    INPUT "Average vehicle age ('1000 op hrs)  ", segdata(26, segcount!, 1)

tryagaina:
    COLOR 14, 1: LOCATE 23, 14: PRINT , "If data is correct press C else E to edit."
    a$ = INPUT$(1)
    IF a$ <> "E" AND a$ <> "e" AND a$ <> "c" AND a$ <> "C" THEN GOTO tryagaina
    IF a$ = "E" OR a$ = "e" THEN GOTO introa
    IF a$ = "c" OR a$ = "C" THEN LOCATE 23, 1: COLOR 1, 1: PRINT "
          "
    CLS : COLOR 7, 1: segcount! = 0

FOR i = 2 TO segm!
  segdata(4, i, 1) = segdata(4, 1, 1): segdata(5, i, 1) = segdata(5, 1, 1): segdata(6, i, 1) = segdata(6, 1, 1)
  segdata(7, i, 1) = segdata(7, 1, 1): segdata(26, i, 1) = segdata(26, 1, 1)
NEXT i

moresegin:
segcount! = segcount! + 1

intro2:
CLS : COLOR 2, 1: PRINT "Please input values at prompt for each segment specified previously"
PRINT : PRINT "SEGMENT "; segcount!: COLOR 7, 1:
IF segcount! > segm! GOTO datainfin
    INPUT "Segment name                       ", segname$(segcount!)
    INPUT "Length of segment (km)              ", segdata(1, segcount!, 1)
    INPUT "Width of road (m)                  ", segdata(2, segcount!, 1) `
    INPUT "Grade of road (%) (uphill positive) ", segdata(3, segcount!, 1)
    INPUT "Average segment speed (20-50kph)    ", segdata(17, segcount!, 1)
    INPUT "Daily tonnage hauled (kt)           ", segdata(8, segcount!, 1)
    PRINT : COLOR 2, 1: PRINT "Material properties of section": COLOR 7, 1
    INPUT "Material type, 1-mixes, 0-fericrete ", segdata(9, segcount!, 1)
    INPUT "California Bearing Ratio (%) CBR    ", segdata(10, segcount!, 1)
    INPUT "Shrinkage product (SP)              ", segdata(11, segcount!, 1)
    INPUT "Grading coefficient (GC)            ", segdata(12, segcount!, 1)
    INPUT "Dust ratio (DR)                    ", segdata(13, segcount!, 1)
    INPUT "Plasticity index (PI)              ", segdata(14, segcount!, 1)
```

```
tryagain2:
     COLOR 14, 1: LOCATE 23, 14: PRINT , "If data is correct press C else E to edit."
     a$ = INPUT$(1)
     IF a$ <> "E" AND a$ <> "e" AND a$ <> "c" AND a$ <> "C" THEN GOTO tryagain2
     IF a$ = "E" OR a$ = "e" THEN GOTO intro2
     IF a$ = "c" OR a$ = "C" THEN LOCATE 23, 1: COLOR 1, 1: PRINT " ": COLOR 7, 1
FOR inrow = 44 TO 89 STEP 9:segcount! = segcount! + 1:IF segcount! > segm! GOTO intro3

introb:
     COLOR 2, 1
     LOCATE 3, inrow: PRINT ; segcount: COLOR 7, 1
     LOCATE 4, inrow: INPUT ; "", segname$(segcount!)
     LOCATE 5, inrow: INPUT ; "", segdata(1, segcount!, 1)
     LOCATE 6, inrow: INPUT ; "", segdata(2, segcount!, 1)
     LOCATE 7, inrow: INPUT ; "", segdata(3, segcount!, 1)
     LOCATE 8, inrow: INPUT ; "", segdata(17, segcount!, 1)
     LOCATE 9, inrow: INPUT ; "", segdata(8, segcount!, 1)
     LOCATE 12, inrow: INPUT ; "", segdata(9, segcount!, 1)
     LOCATE 13, inrow: INPUT ; "", segdata(10, segcount!, 1)
     LOCATE 14, inrow: INPUT ; "", segdata(11, segcount!, 1)
     LOCATE 15, inrow: INPUT ; "", segdata(12, segcount!, 1)
     LOCATE 16, inrow: INPUT ; "", segdata(13, segcount!, 1)
     LOCATE 17, inrow: INPUT ; "", segdata(14, segcount!, 1)

tryagainb:
     COLOR 14, 1: LOCATE 23, 14: PRINT , "If data is correct press C else E to edit."
     a$ = INPUT$(1)
     IF a$ <> "E" AND a$ <> "e" AND a$ <> "c" AND a$ <> "C" THEN GOTO tryagainb
     IF a$ = "E" OR a$ = "e" THEN GOTO introb
     IF a$ = "c" OR a$ = "C" THEN LOCATE 23, 1: COLOR 1, 1: PRINT "
          "
IF segcount! > segm! THEN GOTO intro3
IF segcount! = 5 OR segcount! = 10 OR segcount! = 15 THEN GOTO moresegin
NEXT inrow

'****************************grader water car specs & fleet*****************

intro3:
CLS : COLOR 2, 9
PRINT , "HAUL ROAD MAINTENANCE FLEET DATA SECTION"
COLOR 7, 1: PRINT : INPUT "Enter number of road graders available              "; mfleet(1)
INPUT "Enter grader operating hours per days                 "; mfleet(2)
INPUT "Enter grader total operating cost Rand per hour        "; mfleet(5)
INPUT "Enter number of water-cars available                  "; mfleet(3)
INPUT "Enter water-car operating hours per day                "; mfleet(4)
INPUT "Enter water-car total operating cost Rand per hour      "; mfleet(6)

tryagain3:
COLOR 14, 1: LOCATE 23, 14: PRINT , "If data is correct press C else E to edit."
a$ = INPUT$(1)
IF a$ <> "E" AND a$ <> "e" AND a$ <> "c" AND a$ <> "C" THEN GOTO tryagain3
IF a$ = "E" OR a$ = "e" THEN GOTO intro3
IF a$ = "c" OR a$ = "C" THEN LOCATE 23, 1: COLOR 1, 1: PRINT "
datainfin:
skipabit:

END SUB
```

```
SUB costmodeledit


COLOR 2, 1: PRINT : PRINT , "VEHICLE AND MAINTENANCE FLEET COSTS"
COLOR 7, 1: PRINT : PRINT , "Haul truck operating cost data"
PRINT : PRINT , "1.  Tyre cost (R/km)      TW = "; voccostmod(1); "+"; voccostmod(2); "IRI+";
        voccostmod(3); "GR%"
PRINT , "2.  Parts cost (R/km)  P/VP = ("; voccostmod(4); "+"; voccostmod(5); "IRI)."; "H^";
        voccostmod(6)
PRINT , "3.  Labour cost (R/km)   L = "; voccostmod(7); "(P/VP)^"; voccostmod(8)

redefinecoeff1:
LOCATE 23, 1: COLOR 14, 1
INPUT ; "            Enter model number to modify (1, 2 or 3) or C to continue"; modmod$
IF modmod$ <> "1" AND modmod$ <> "2" AND modmod$ <> "3" AND modmod$ <> "C" AND
        modmod$ <> "c" THEN GOTO redefinecoeff1
IF modmod$ = "1" THEN GOTO do1
IF modmod$ = "2" THEN GOTO do2
IF modmod$ = "3" THEN GOTO do3
IF modmod$ = "c" OR modmod$ = "C" THEN GOTO skip1

do1:
COLOR 7, 1: LOCATE 9, 1: PRINT , "                                                    "
LOCATE 9, 1: INPUT ; "           1.  Tyre cost (R/km)     TW = "; voccostmod(1)
INPUT ; "+"; voccostmod(2)
INPUT ; " IRI+"; voccostmod(3)
PRINT ; "GR%"
GOTO redefinecoeff1

do2:
COLOR 7, 1: LOCATE 10, 1: PRINT , "                                                    "
LOCATE 10, 1: INPUT ; "          2.  Parts cost (R/km) P/VP = ("; voccostmod(4)
INPUT ; "+"; voccostmod(5)
INPUT ; "IRI).H^"; voccostmod(6)
GOTO redefinecoeff1

do3:
COLOR 7, 1: LOCATE 11, 1: PRINT , "                                                    "
LOCATE 11, 1: INPUT ; "          3.  Labour cost (R/km)    L = "; voccostmod(7)
INPUT ; "(P/VP)^"; voccostmod(8)
GOTO redefinecoeff1

skip1:

END SUB
```

```
SUB costmodels

'read default model coefficients into aray
voccostmod(1) = .06        'tyre model
voccostmod(2) = .012
voccostmod(3) = .002
voccostmod(4) = 4          'parts model
voccostmod(5) = 20
voccostmod(6) = .375
voccostmod(7) = 220        'labour model
voccostmod(8) = .45

CLS : COLOR 2, 1: PRINT , "VEHICLE AND MAINTENANCE FLEET COSTS"

tryagain4:
LOCATE 3, 1: COLOR 7, 1:  PRINT , "Do you want to change any cost estimate equations (Y/N)?"
a$ = INPUT$(1)
IF a$ <> "Y" AND a$ <> "y" AND a$ <> "n" AND a$ <> "N" THEN GOTO tryagain4
IF a$ = "Y" OR a$ = "y" THEN CALL costmodeledit

intro5:
CLS : COLOR 2, 1:  PRINT , "UNIT COST FACTORS"
COLOR 7, 1: PRINT
PRINT , "Parts and labour costs are based on 1995 prices"
INPUT ; "              Please specify escalation factor"; voccostmod(9)

tryagain7:
COLOR 14, 1: LOCATE 23, 14: PRINT , "If data is correct press C else E to edit."
a$ = INPUT$(1)
IF a$ <> "E" AND a$ <> "e" AND a$ <> "c" AND a$ <> "C" THEN GOTO tryagain7
IF a$ = "E" OR a$ = "e" THEN GOTO intro5
IF a$ = "c" OR a$ = "C" THEN LOCATE 23, 1: COLOR 1, 1: PRINT "

intro6:
COLOR 7, 1: LOCATE 6, 1: PRINT , "Fuel cost is based on a current diesel price "
INPUT ; "              Please specify diesel price Rand per litre"; voccostmod(10)

tryagain8:
COLOR 14, 1: LOCATE 23, 14: PRINT , "If data is correct press C else E to edit."
a$ = INPUT$(1)
IF a$ <> "E" AND a$ <> "e" AND a$ <> "c" AND a$ <> "C" THEN GOTO tryagain8
IF a$ = "E" OR a$ = "e" THEN GOTO intro6
IF a$ = "c" OR a$ = "C" THEN LOCATE 23, 1: COLOR 1, 1: PRINT "  ":COLOR 7, 1

intro7:
COLOR 7, 1: LOCATE 9, 1: PRINT , "Tyre cost is based on current tyre price "
INPUT ; "              Please specify tyre price (R)"; voccostmod(11)

tryagain9:
COLOR 14, 1: LOCATE 23, 14: PRINT , "If data is correct press C else E to edit."
a$ = INPUT$(1)
IF a$ <> "E" AND a$ <> "e" AND a$ <> "c" AND a$ <> "C" THEN GOTO tryagain9
IF a$ = "E" OR a$ = "e" THEN GOTO intro7
IF a$ = "c" OR a$ = "C" THEN LOCATE 23, 1: COLOR 1, 1: PRINT "              ":COLOR 7, 1

END SUB
```

```
SUB speed

'For calculation of vehicle speed prior to fuel consumption assessment
CLS

FOR segment = 1 TO segm!
    rdsmin = 31.1919 - (.05354 * segdata(11, segment, 1)) - (.0152 * segdata(10, segment, 1))
    rdsmax = 7.6415 + (.4215 * segdata(8, segment, 1)) + (.3133 * segdata(12, segment, 1)) + (.4952
        * rdsmin)
    rrmin = EXP(-1.7166 + .0028 * segdata(17, segment, 1))
     'PRINT ; "days  "; "rds     "; "trladen   "; " trunladen "; "  rr%; "; "  vladen   "; "  vunladen  "
     PRINT ; "days  "; "      trl "; "      tru "; "   vl  "; "     vu  "; "      fa    "; "  fb       "; " fc       "; "fd
      "; "ftot"

    FOR days = 0 TO 20

        rdi = 1.768 + .001 * days * (2.69 * segdata(8, segment, 1) - 72.75 * segdata(14, segment, 1)
            - 2.59 * segdata(10, segment, 1) - 9.35 * segdata(12, segment, 1) + 1.67 * segdata(11,
            segment, 1))
        segdata(15, segment, (days + 1)) = rdsmin + ((rdsmax - rdsmin) / (1 + EXP(rdi)))

        ldrri = -6.368 - .00685 * segdata(15, segment, (days + 1)) + .0061 * segdata(17, segment, 1)
        segdata(16, segment, (days + 1)) = 100 * (rrmin + segdata(15, segment, (days + 1)) *
            EXP(ldrri)) / 9.81
        segdata(18, segment, (days + 1)) = segdata(16, segment, (days + 1)) + segdata(3, segment, 1)
        segdata(19, segment, (days + 1)) = segdata(16, segment, (days + 1)) - segdata(3, segment, 1)

     'speed
        IF SGN(segdata(18, segment, (days + 1))) = -1 THEN segdata(20, segment, (days + 1)) = 5
            + (49 / (1 + EXP((9.5 + ABS(segdata(18, segment, (days + 1)))) / -2.4))) ELSE segdata(20,
            segment, (days + 1)) = 9 + (55 / (1 + EXP((-2.25 + _
            segdata(18, segment, (days + 1))) / 1.75)))
        IF SGN(segdata(19, segment, (days + 1))) = 1 THEN segdata(21, segment, (days + 1)) = 20
            + (35 / (1 + EXP((-6.31 + segdata(19, segment, (days + 1))) / 1.9))) ELSE segdata(21,
            segment, (days + 1)) = 13 + (42 / (1 + EXP((10.03 + ABS( _
            segdata(19, segment, (days + 1)))) / -.803)))

    'fuel
        fa = 0: fb = 0: fc = 0: fd = 0
        IF SGN(segdata(18, segment, (days + 1))) = -1 THEN fa = -3.575 + segdata(5, segment, 1)
            * (.092 - .016 * segdata(6, segment, 1) + .0017 * segdata(4, segment, 1))
        IF SGN(segdata(18, segment, (days + 1))) = 1 THEN fb = segdata(5, segment, 1) * segdata(20,
            segment, (days + 1)) * (296 * segdata(18, segment, (days + 1)) + 4.5 * segdata(20, segment,
            (days + 1)))
        IF SGN(segdata(18, segment, (days + 1))) = 1 THEN fb = fb + segdata(4, segment, 1) *
            segdata(20, segment, (days + 1)) * (246 * segdata(18, segment, (days + 1)) + .027 *
            (segdata(20, segment, (days + 1))) ^ 2)
        IF SGN(segdata(18, segment, (days + 1))) = 1 THEN fb = 1.02 + .00001 * fb

        IF SGN(segdata(19, segment, (days + 1))) = -1 THEN fc = -3.575 + segdata(5, segment, 1)
            * (.092 - .016 * segdata(6, segment, 1))
        IF SGN(segdata(19, segment, (days + 1))) = 1 THEN fd = segdata(5, segment, 1) * segdata(21,
            segment, (days + 1)) * (296 * segdata(19, segment, (days + 1)) + 4.5 * segdata(21, segment,
            (days + 1)))
        IF SGN(segdata(19, segment, (days + 1))) = 1 THEN fd = 1.02 + .00001 * fd
```

```
'convert to l/km consumption

        fa = 1 / (segdata(20, segment, (days + 1)) / 3600) * fa / 1000
        fb = 1 / (segdata(20, segment, (days + 1)) / 3600) * fb / 1000
        fc = 1 / (segdata(21, segment, (days + 1)) / 3600) * fc / 1000
        fd = 1 / (segdata(21, segment, (days + 1)) / 3600) * fd / 1000

'total fuel cost for fleet to move segment tonnage

        segdata(22, segment, (days + 1)) = voccostmod(10) * (segdata(1, segment, 1) * (segdata(8,
           segment, 1) * 1000 / (segdata(4, segment, 1) - segdata(5, segment, 1))) * (fa + fb + fc +
           fd))

PRINT USING " ####.##"; days; segdata(18, segment, (days + 1)); segdata(19, segment, (days + 1));
           segdata(20, segment, (days + 1)); segdata(21, segment, (days + 1)); fa; fb; fc; fd;
           segdata(22, segment, (days + 1))

    NEXT days
    a$ = INPUT$(1)
    CLS
NEXT segment

END SUB
```

```
SUB othercost

' For tyre, parts and labour cost estimation

CLS

FOR segment = 1 TO segm!

PRINT ; "    days"; "    tw "; "  TWtot"; "    P/kkm"; "    Ptot  "; " L/kkm    "; " Ltot"
      FOR days = 0 TO 20

            'tyre wear costs

            tw = (voccostmod(1) + voccostmod(2) * (3.0556 + .0641 * segdata(15, segment, (days + 1)))
                + voccostmod(3) * ABS(segdata(3, segment, 1)))
            segdata(23, segment, (days + 1)) = (tw * voccostmod(11) / 1000) * 2 * (segdata(1, segment, 1)
                * (segdata(8, segment, 1) * 1000 / (segdata(4, segment, 1) - segdata(5, segment, 1))))

            'parts costs

            p1 = (voccostmod(4) + (voccostmod(5) * (3.0556 + .0641 * segdata(15, segment, (days + 1)))))
                * (segdata(26, segment, 1)) ^ voccostmod(6)
            p = voccostmod(9) * 10 * segdata(7, segment, 1) * p1
            segdata(24, segment, (days + 1)) = (p / 1000) * 2 * (segdata(1, segment, 1) * (segdata(8,
                segment, 1) * 1000 / (segdata(4, segment, 1) - segdata(5, segment, 1))))

            'labour cost

            l = voccostmod(9) * voccostmod(7) * p1 ^ voccostmod(8)
            segdata(25, segment, (days + 1)) = (l / 1000) * 2 * (segdata(1, segment, 1) * (segdata(8,
                segment, 1) * 1000 / (segdata(4, segment, 1) - segdata(5, segment, 1))))


  PRINT USING " ####.##"; days; tw; segdata(23, segment, (days + 1)); p1; segdata(24, segment, (days +
                1)); l; segdata(25, segment, (days + 1))

      NEXT days
       a$ = INPUT$(1)
       CLS
NEXT segment

END SUB
```

P-13

```
SUB totalvoccost

'To calculate total vehicle operating costs

segment = 0: segplace = 0

moretotals:
IF segment = 6 OR segment = 12 OR segment = 18 THEN segplace = segplace - 6
CLS : COLOR 2, 1: PRINT , "TOTAL DAILY VOC PER SEGMENT FOR "; minename$:  PRINT ; "Days"
FOR days = 0 TO 20: PRINT ; days: NEXT days

moresegments:
IF segment = segm! THEN GOTO out2
segment = segment + 1: segplace = segplace + 1

FOR days = 0 TO 20
    segdata(27, segment, (days + 1)) = segdata(22, segment, (days + 1)) + segdata(23, segment, (days +
       1)) + segdata(24, segment, (days + 1)) + segdata(25, segment, (days + 1))
    COLOR 2, 1: LOCATE 2, (segplace * 10): PRINT ; segname$(segment)
    COLOR 7, 1: LOCATE (3 + days), (segplace * 10): PRINT USING "#####.##"; segdata(27, segment,
       (days + 1))

NEXT days
    COLOR 14, 1: LOCATE 23, 54: PRINT "Hit any key to continue": a$ = INPUT$(1): LOCATE 23, 54:
COLOR 1, 1: PRINT , "                        "
    IF segment = 6 OR segment = 12 OR segment = 18 GOTO moretotals
    IF segment < segm! THEN GOTO moresegments

out2:

END SUB
```

```
SUB maintcost

FOR segment = 1 TO segm!
   totkm = totkm + segdata(1, segment, 1)
      FOR days = 0 TO 20
            IF segdata(15, segment, (days + 1)) > 45 THEN gradprod = .75 - .004625 * (segdata(15,
                segment, (days + 1)) - 45) ELSE gradprod = .75
            'total segment daily cost for x days interval between
            segdata(28, segment, (days + 1)) = ((mfleet(5) / gradprod) + (mfleet(6) / 6.3)) * segdata(1,
                segment, 1) / (days + 1)
      NEXT days
NEXT segment

segment = 0: segplace = 0

moremtotals:
IF segment = 6 OR segment = 12 OR segment = 18 THEN segplace = segplace - 6
CLS : COLOR 2, 1: PRINT , "TOTAL DAILY MAINTENANCE COST PER SEGMENT FOR ";
minename$:  PRINT ; "Days"
FOR days = 0 TO 20: PRINT ; days: NEXT days

moremsegments:
IF segment = segm! THEN GOTO out1
segment = segment + 1: segplace = segplace + 1

FOR days = 0 TO 20
     COLOR 2, 1: LOCATE 2, (segplace * 10): PRINT ; segname$(segment)
     COLOR 7, 1: LOCATE (3 + days), (segplace * 10): PRINT USING "#####.##"; segdata(28, segment,
        (days + 1))
NEXT days

     COLOR 14, 1: LOCATE 23, 54: PRINT "Hit any key to continue": a$ = INPUT$(1): LOCATE 23, 54:
COLOR 1, 1: PRINT , "                              "
     IF segment = 6 OR segment = 12 OR segment = 18 GOTO moremtotals
     IF segment < segm! THEN GOTO moremsegments

out1:

CLS : COLOR 2, 1: PRINT "MAINTENANCE FLEET PRODUCTIVITY."
PRINT
FOR days = 0 TO 20: PRINT ; days: NEXT days
FOR days = 0 TO 20

   COLOR 2, 1: LOCATE 2, 10: PRINT ; "Reqd km/day": LOCATE 2, 25: PRINT ; "Graded km/day":
   LOCATE 2, 40: PRINT ; "Watered km/day"

      FOR segment = 1 TO segm!
         IF segdata(15, segment, (days + 1)) > 45 THEN gradprod = .75 - .004625 * (segdata(15, segment,
               (days + 1)) - 45) ELSE gradprod = .75
         graderhrs = graderhrs + (segdata(1, segment, 1) / gradprod)
         waterhrs = waterkhrs + (segdata(1, segment, 1) / 6.3)
      NEXT segment
         graderkm = totkm * mfleet(1) * mfleet(2) / graderhrs
         waterkm = totkm * mfleet(3) * mfleet(4) / waterhrs
         COLOR 7, 1: LOCATE (3 + days), 10: PRINT USING "##.###"; totkm / (days + 1)
         COLOR 7, 1: LOCATE (3 + days), 25: PRINT USING "####.##"; graderkm
         LOCATE (3 + days), 40: PRINT USING "####.##"; waterkm
         graderhrs = 0: waterhrs = 0
```

```
NEXT days

    COLOR 14, 1: LOCATE 23, 54: PRINT "Hit any key to continue": a$ = INPUT$(1): LOCATE 23, 54:
COLOR 1, 1: PRINT , "                    "

END SUB


SUB tot

' To calculate unoptimised total daily cost per segment

segment = 0: segplace = 0

moretots:
IF segment = 6 OR segment = 12 OR segment = 18 THEN segplace = segplace - 6
CLS : COLOR 2, 1: PRINT , "UNOPTIMISED TOTAL DAILY COST PER SEGMENT FOR "; minename$:
PRINT ; "Days"
FOR days = 0 TO 20: PRINT ; days: NEXT days

moretotsegments:
IF segment = segm! THEN GOTO out3
segment = segment + 1: segplace = segplace + 1

FOR days = 0 TO 20
    COLOR 2, 1: LOCATE 2, (segplace * 10): PRINT ; segname$(segment)
    COLOR 7, 1: LOCATE (3 + days), (segplace * 10): PRINT USING "#####.##"; segdata(27, segment,
            (days + 1)) + segdata(28, segment, (days + 1))
NEXT days

    COLOR 14, 1: LOCATE 23, 54: PRINT "Hit any key to continue": a$ = INPUT$(1): LOCATE 23, 54:
    COLOR 1, 1: PRINT , "                    "
    IF segment = 6 OR segment = 12 OR segment = 18 GOTO moretots
    IF segment < segm! THEN GOTO moretotsegments


out3:

'total cost for all segments

CLS : COLOR 2, 1: PRINT , "UNOPTIMISED TOTAL DAILY COST FOR "; minename$:   PRINT ;
            "Days"
FOR days = 0 TO 20: PRINT ; days: NEXT days
LOCATE 2, (15): PRINT ; "Total cost R/day"

FOR days = 0 TO 20
    FOR segment = 1 TO segm!
      totcost = totcost + segdata(27, segment, (days + 1)) + segdata(28, segment, (days + 1))
    NEXT segment

    COLOR 7, 1: LOCATE (3 + days), 15: PRINT USING "######.##"; totcost
    totcost = 0
NEXT days

    COLOR 14, 1: LOCATE 23, 54: PRINT "Hit any key to continue": a$ = INPUT$(1): LOCATE 23, 54:
COLOR 1, 1: PRINT , "

END SUB
```

```
SUB optimalsol

'optimal policy selection

'******************************Dimension array****************************

DIM opt(6, segm!)            '1=optimal total cost
                            '2=optimal dats interval
                            '3=grader productivity for optimal
                            '4=rate of change

mm = 0:CLS
COLOR 2, 1: PRINT , "OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR "; minename$
PRINT : PRINT , "Segment", "Optimum total", , "Optimum maintenance"
PRINT , , "daily cost (R)", "interval (days)": PRINT

FOR segment = 1 TO segm!
      opt(1, segment) = 1000000!

      FOR days = 0 TO 20
      totcost = segdata(27, segment, (days + 1)) + segdata(28, segment, (days + 1))
      IF opt(1, segment) > totcost THEN GOTO swop ELSE GOTO jumpnext
swop:
      opt(1, segment) = totcost: opt(2, segment) = days + 1

jumpnext:
      NEXT days
      COLOR 7, 1: PRINT , segname$(segment), opt(1, segment), , opt(2, segment) - 1
      NEXT segment

'calculate reqd and available grader hrs

totkm = 0: totgrhrs = 0: totopcost = 0

FOR segment = 1 TO segm!
      totkm = totkm + segdata(1, segment, 1)
      IF segdata(15, segment, opt(2, segment)) > 45 THEN gradprod = .75 - .004625 * (segdata(15, segment,
        opt(2, segment)) - 45) ELSE gradprod = .75
      opt(3, segment) = (segdata(1, segment, 1) / gradprod) / opt(2, segment)
      totgrhrs = totgrhrs + opt(3, segment)
      totopcost = totopcost + opt(1, segment)
NEXT segment

availgrhrs = mfleet(1) * mfleet(2)

decidefeas:

IF availgrhrs > totgrhrs GOTO feas

COLOR 4, 1: PRINT : PRINT , "     Infeasible optimal solution since required grading hours per day"
PRINT USING "     exceeds available grader hours by ##.## hrs."; totgrhrs - availgrhrs
IF opt(2, chrateseg) = 20 THEN GOTO jumpout
a$ = INPUT$(1)
GOTO newoptsolution

feas:
COLOR 4, 1: PRINT : PRINT "     Feasible optimal solution. "
COLOR 7, 1: PRINT : PRINT USING "     ##.## grader hrs required per day.  ##.## grader hrs available.";
```

```
        totgrhrs; availgrhrs
PRINT "     Minimum total cost solution equates to a VOC and road maintenance"
PRINT USING "     combined cost of R#####.## per day."; totopcost

FOR segment = 1 TO segm!
     IF opt(2, segment) - 1 = 20 THEN GOTO print2:NEXT segment:GOTO found

print20:
PRINT : PRINT ; "     A maintenance interval of 20 days is the maximum range analysed."
PRINT ; "     Maintenance at shorter interval for these sections will increase"
PRINT ; "     costs only marginally"

GOTO found

newoptsolution:
' find segment with lowest rate of change in total cost and  extend interval by 1 day

chrate = 1000000!
FOR segment = 1 TO segm!
     opt(4, segment) = segdata(27, segment, (opt(2, segment) + 1)) + segdata(28, segment, (opt(2, segment)
       + 1)) - opt(1, segment)
          PRINT segdata(27, segment, (opt(2, segment) + 1)), segdata(28, segment, (opt(2, segment) + 1)),
               opt(1,segment), opt(4, segment)
     IF opt(4, segment) < chrate THEN GOTO swop1 ELSE GOTO jumpnext1

swop1:
     chrate = opt(4, segment): chrateseg = segment

jumpnext1:
     NEXT segment

opt(2, chrateseg) = opt(2, chrateseg) + 1
opt(1, chrateseg) = segdata(27, chrateseg, opt(2, chrateseg)) + segdata(28, chrateseg, opt(2, chrateseg))


'recalculate totgrhrs with new additional maintenance interval

totkm = 0: totgrhrs = 0: totopcost = 0:CLS

COLOR 2, 1: PRINT , "OPTIMAL MAINTENANCE FREQUENCY SOLUTION FOR "; minename$
PRINT : PRINT , "Segment", "Optimum total", , "Optimum maintenance"
PRINT , , "daily cost (R)", "interval (days)": PRINT

FOR segment = 1 TO segm!
     totkm = totkm + segdata(1, segment, 1)
     IF segdata(15, segment, opt(2, segment)) > 45 THEN gradprod = .75 - .004625 * (segdata(15, segment,
       opt(2, segment)) - 45) ELSE gradprod = .75
     opt(3, segment) = (segdata(1, segment, 1) / gradprod) / opt(2, segment)
     totgrhrs = totgrhrs + opt(3, segment)
     totopcost = totopcost + opt(1, segment)
     COLOR 7, 1: PRINT , segname$(segment), opt(1, segment), , opt(2, segment) - 1
NEXT segment

GOTO decidefeas

jumpout:
found:
END SUB
```

MMS MODEL PROGRAM DATA - KROMDRAAI COLLIERY

DATA	KROMDRAAI COLLIERY		
	Main-tip	HR2	HR3
Length (km)	1,13	3,24	4,53
Grade (%)	-0,4	0,99	0,55
GVM (t)	217	217	271
UVM(t)	111	111	111
Drive system	1	1	1
Vehicle price (Rm)	1,83	1,83	1,83
Vehicle age ('000hrs)	1,24	1,24	1,24
Daily tonnage (kt)	15	7,7	7,3
Material type	0	0	0
CBR	46	50	162
SP	198	196	82
GC	36,3	21,3	30,1
DR	0,6	0,6	0,4
PI	10	8	4
Grader fleet	3		
Grader op hrs/day	8,2		
Cost R/op hrs	62		
Water-car fleet	2		
Water-car op hrs/day	6,5		
Cost R/op hrs	119		

MMS MODEL PROGRAM DATA - KRIEL COLLIERY

DATA	KRIEL COLLIERY			
	Main-HR	R6/10	R7	R8/11
Length (km)	4,6	1,92	2,19	3,78
Grade (%)	1,51	0,91	1,43	0,96
GVM (t)	274	274	274	274
UVM(t)	120	120	120	120
Drive system	1	1	1	1
Vehicle price (Rm)	1,7	1,7	1,7	1,7
Vehicle age ('000hrs)	11,86	11,86	11,86	11,86
Daily tonnage (kt)	16,74	3,77	8,84	4,13
Material type	0	1	1	1
CBR	98	48	132	132
SP	102	160	111	111
GC	24,8	30,9	30,7	30,7
DR	0,4	0,6	0,5	0,5
PI	4	8	6	6
Grader fleet	2			
Grader op hrs/day	9,4			
Cost R/op hrs	66,4			
Water-car fleet	1			
Water-car op hrs/day	10,1			
Cost R/op hrs	78,1			

MMS MODEL PROGRAM DATA - KLEINKOPJE COLLIERY

DATA	KLEINKOPJE COLLIERY						
	Main-tip	5W& ramp	R13 /14	2A9	2A8	2A7	3A
Length (km)	0,5	3,21	2,85	2,2	1,39	0,94	2,27
Grade (%)	0,2	2,81	2,17	2,73	1,23	1,43	0,18
GVM (t)	274	274	274	274	274	274	274
UVM(t)	120	120	120	120	120	120	120
Drive system	1	1	1	1	1	1	1
Vehicle price (Rm)	1,7	1,7	1,7	1,7	1,7	1,7	1,7
Vehicle age ('000hrs)	5	5	5	5	5	5	5
Daily tonnage (kt)	18,6	6,7	7,7	4,2	1,4	1,4	9,7
Material type	0	0	0	0	0	0	0
CBR	79	79	79	79	79	79	79
SP	164,5	164,5	164,5	178,5	178,5	178,5	178,5
GC	28,8	28,8	28,8	27,7	27,7	27,7	27,7
DR	0,6	0,6	0,6	0,5	0,5	0,5	0,5
PI	7	7	7	7	7	7	7
Grader fleet	3						
Grader op hrs/day	3,9						
Cost R/op hrs	68,4						
Water-car fleet	2						
Water-car op hrs/day	6,4						
Cost R/op hrs	74,5						

MMS MODEL PROGRAM DATA - NEW VAAL COLLIERY

DATA	NEW VAAL COLLIERY									
	Main-tip	**MR0-R2**	**MR2-R3**	**MR3-R4**	**R4-R6/7**	**R6/7-R9**	**R0**	**R2**	**R3**	**R4**
Length (km)	0,57	1,58	1,01	0,7	0,8	1,09	0,65	0,49	0,83	0,64
Grade (%)	1,14	0,18	0,5	0,39	-0,93	2,53	2,92	3,47	2,53	4,38
GVM (t)	274	274	274	274	274	274	274	274	274	274
UVM(t)	120	120	120	120	120	120	120	120	120	120
Drive system	1	1	1	1	1	1	1	1	1	1
Vehicle price (Rm)	1,7	1,7	1,7	1,7	1,7	1,7	1,7	1,7	1,7	1,7
Vehicle age ('000hrs)	14,4	14,4	14,4	14,4	14,4	14,4	14,4	14,4	14,4	14,4
Daily tonnage (kt)	51	32,7	23,8	16	14	5,05	18,8	8,9	7,78	1,9
Material type	1	1	1	1	1	1	1	1	1	1
CBR	94	94	55	55	49	49	49	49	49	49
SP	90	90	128	128	72	72	72	72	72	72
GC	31,1	31,3	28,7	28,7	26,7	26,7	26,7	26,7	26,7	26,7
DR	0,4	0,4	0,5	0,5	0,4	0,4	0,4	0,4	0,4	0,4
PI	5	5	8	8	5	5	5	5	5	5
Grader fleet	3									
Grader op hrs/day	7,7									
Cost R/op hrs	64,7									
Water-car fleet	2									
Water-car op hrs/day	9,2									
Cost R/op hrs	82,2									