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 <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
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 <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 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.

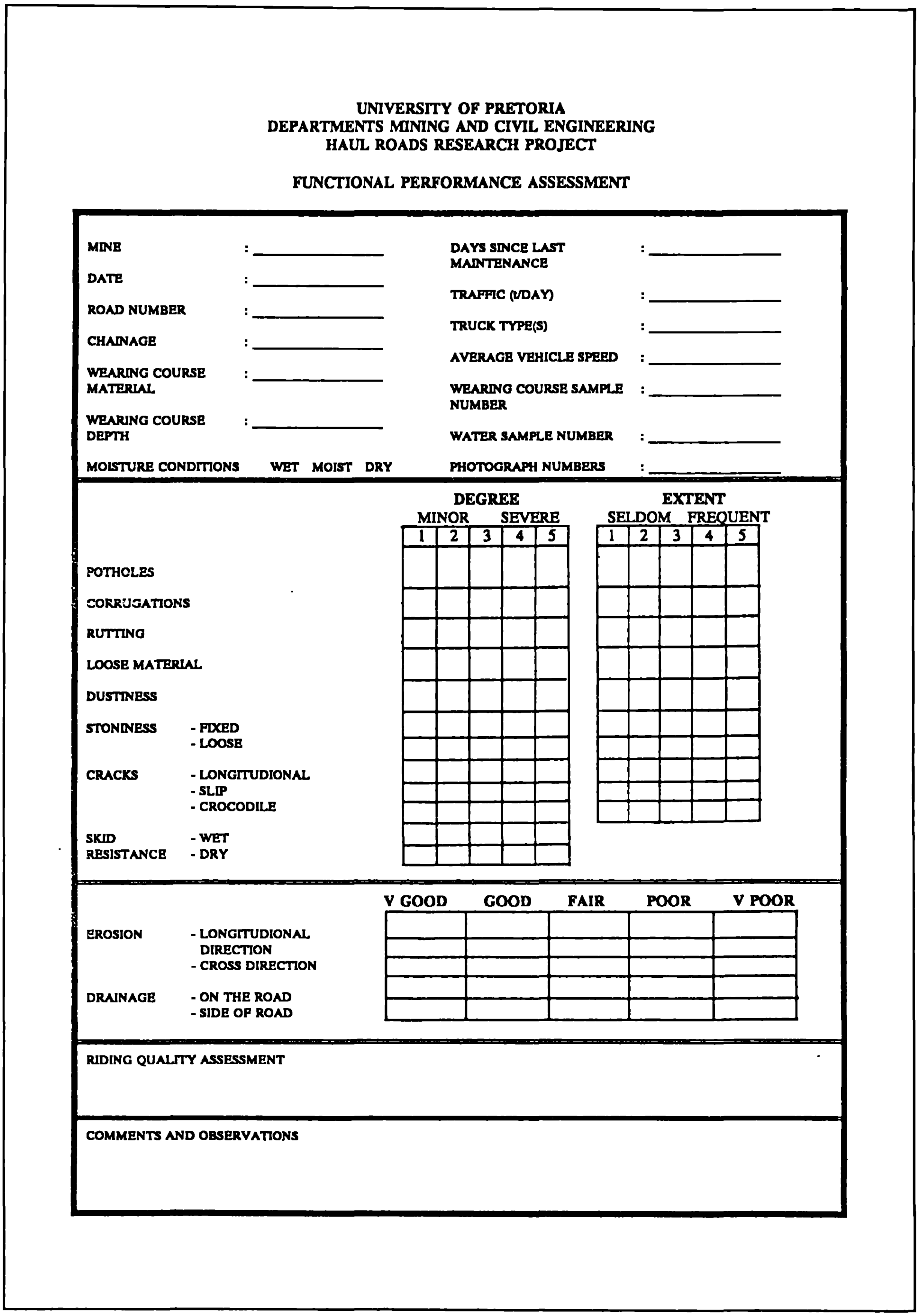
9.2.1.10 Drainage (on Road and Roadside)

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					EXTENT				
		MINOR				SEVERE	SELDOM				FREQUENT
		1	2	3	4	5	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.

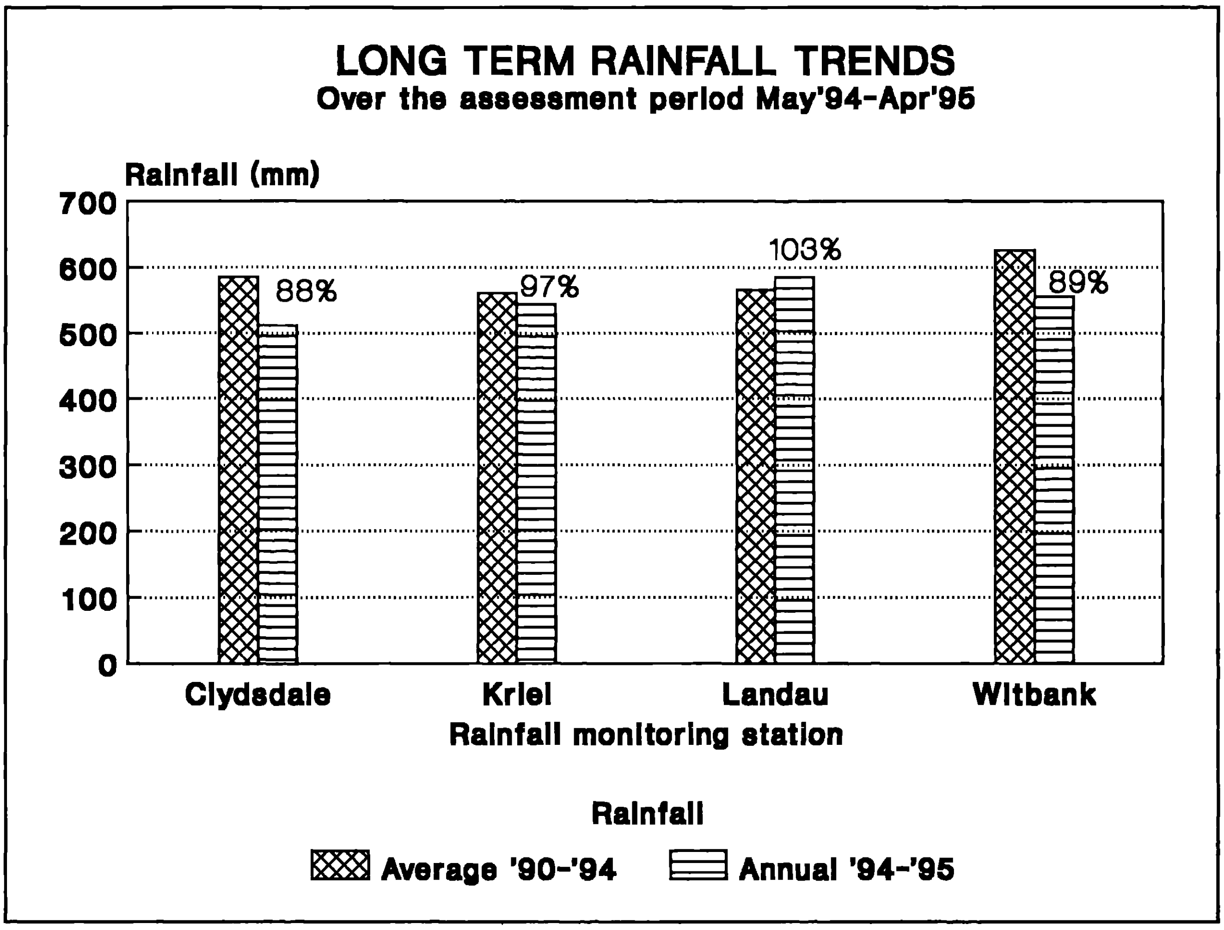


Figure 9.2 Long Term rainfall trends for Stations in the Vicinity of Mine Test Sites

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.

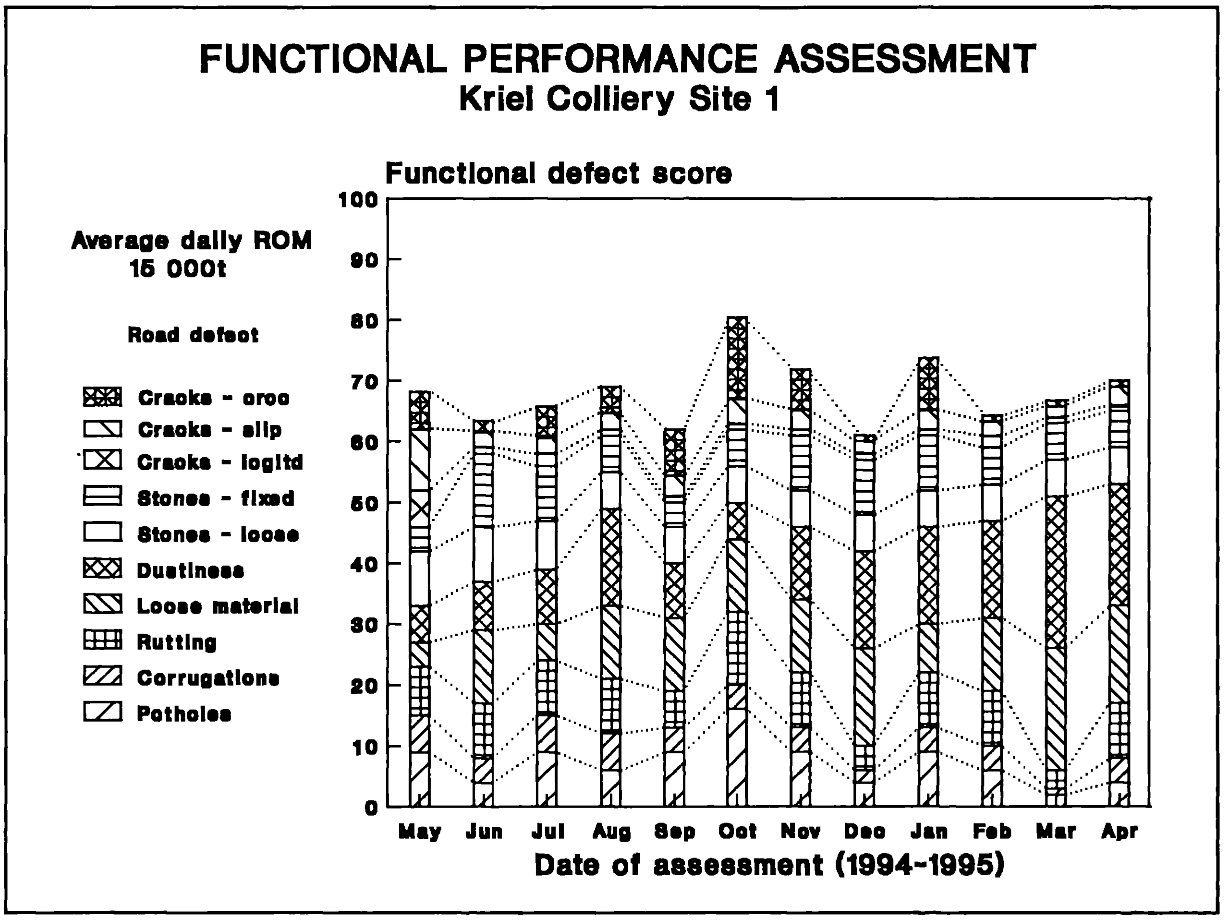


Figure 9.3 Functional Performance Assessment, Kriel Colliery Site 1

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.

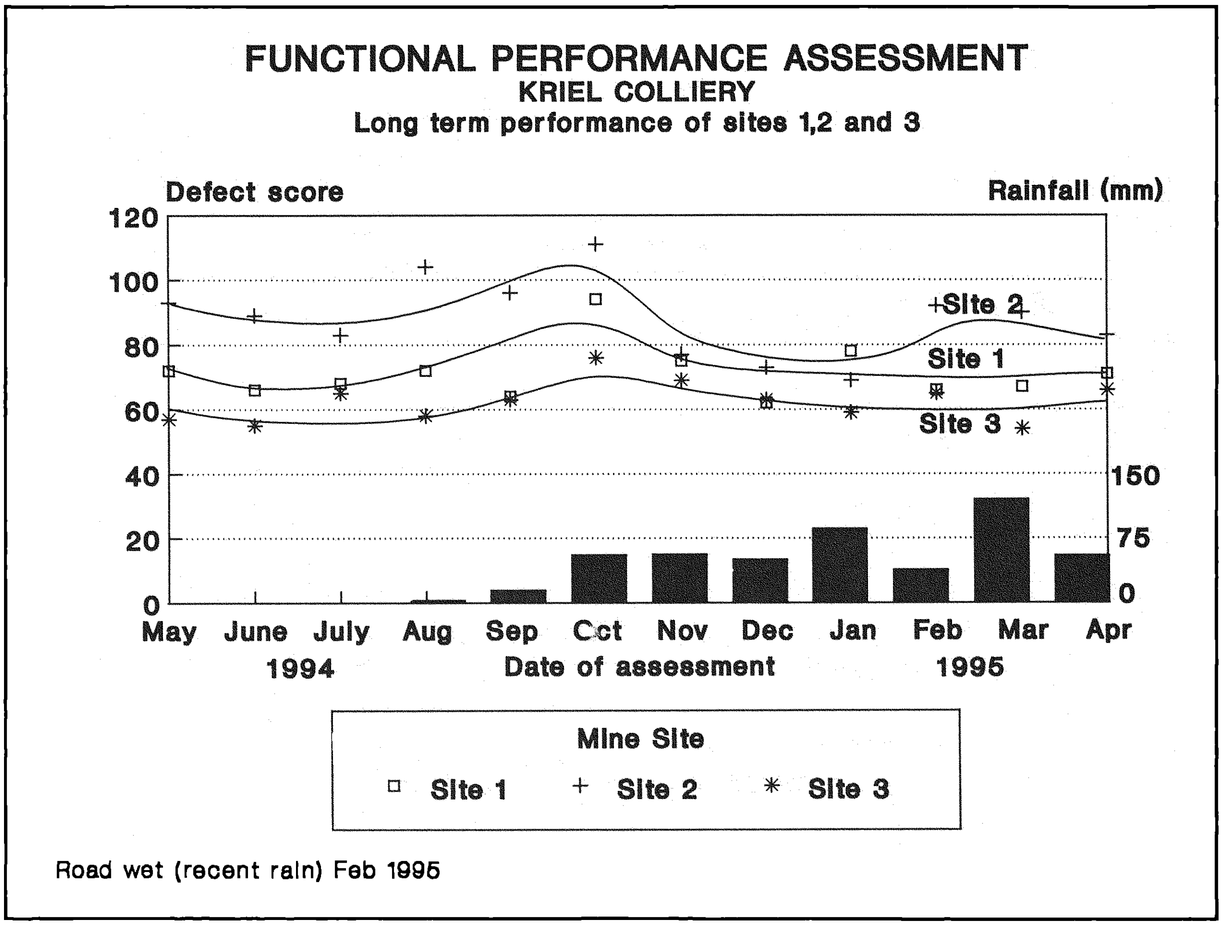


Figure 9.4 Long Term Performance Assessment, Kriel Colliery Sites 1, 2 and 3.

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.

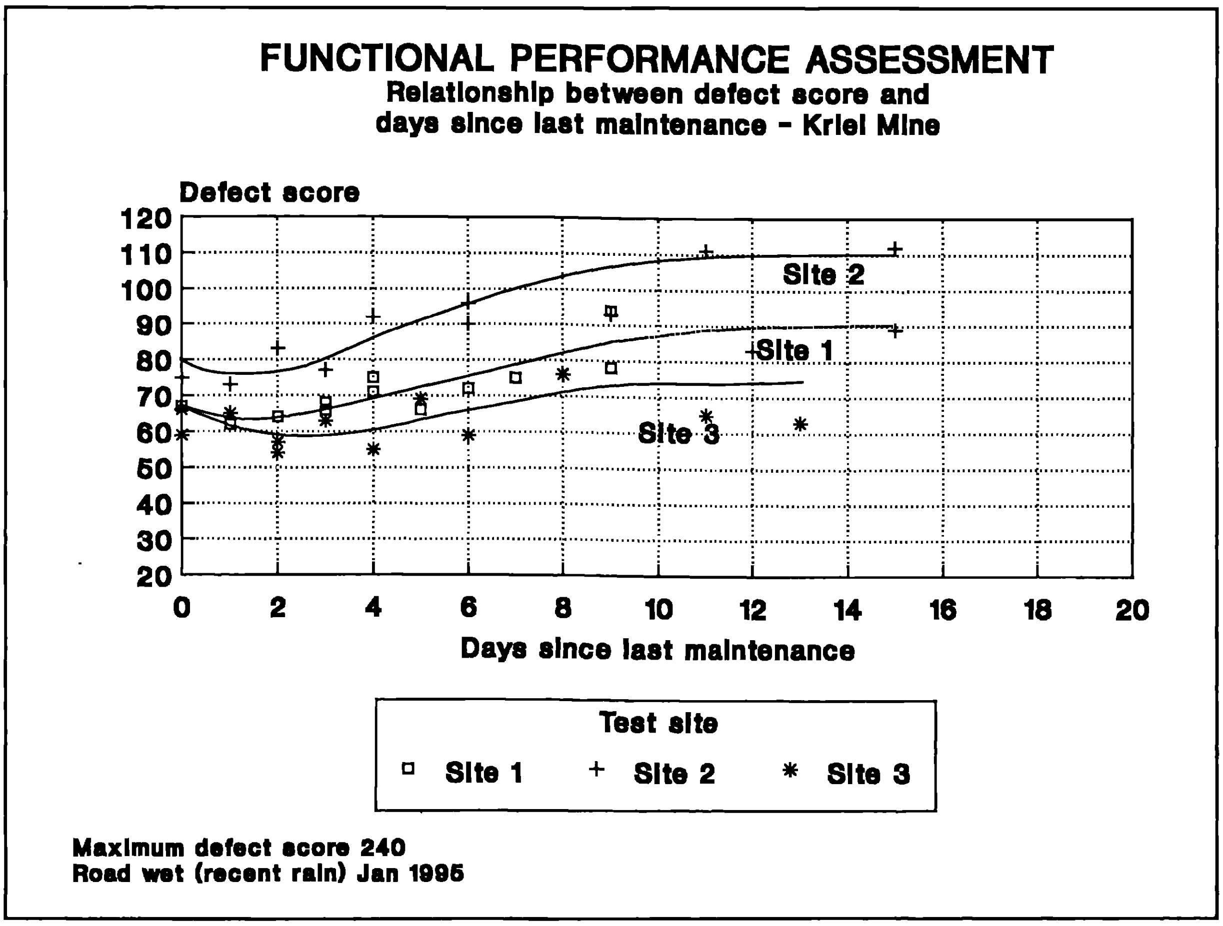


Figure 9.5 Effect of Maintenance on Defect Scores, Kriel Colliery Sites 1, 2 and 3.

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

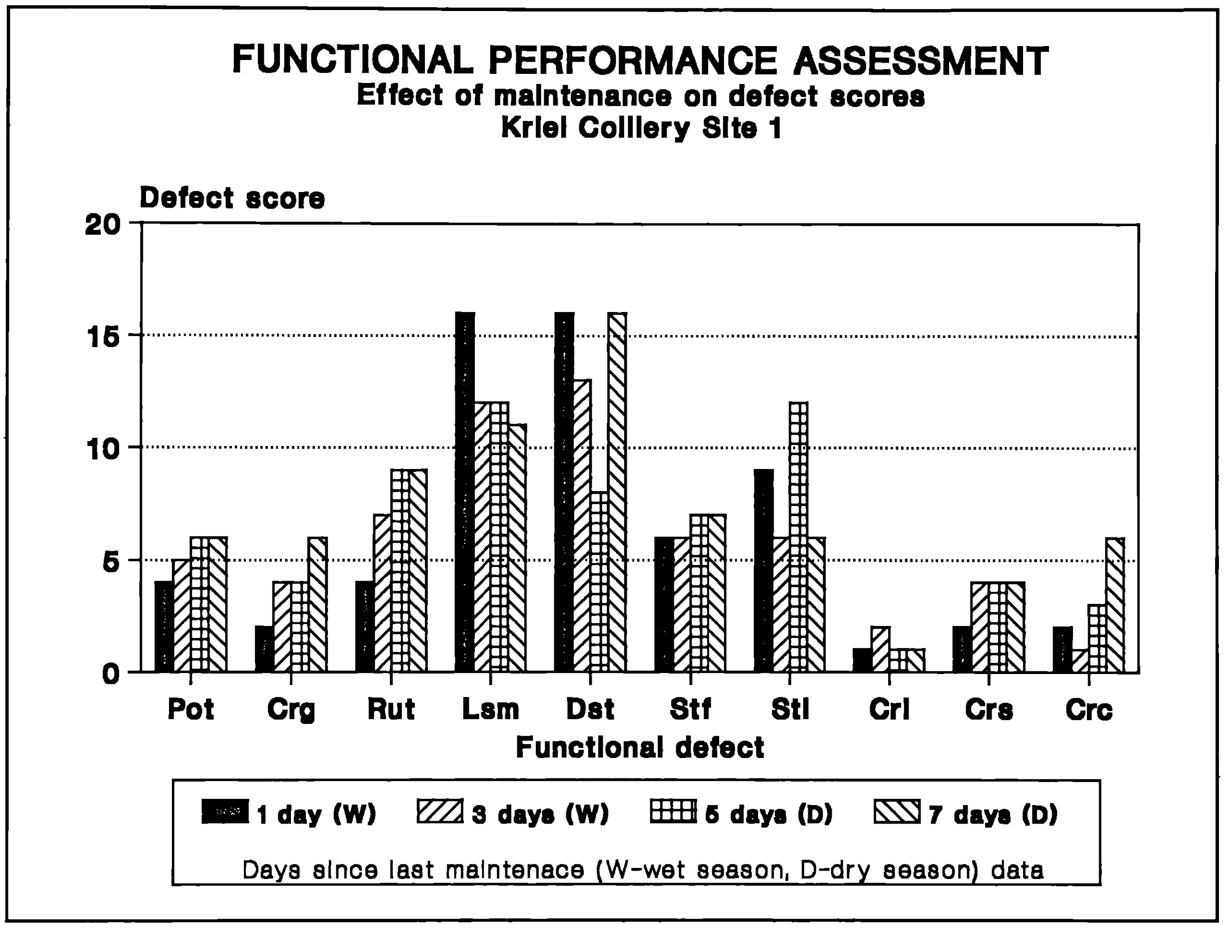


Figure 9.6 Effect of time since last maintenance on defect scores, Kriel Colliery Site 1.

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

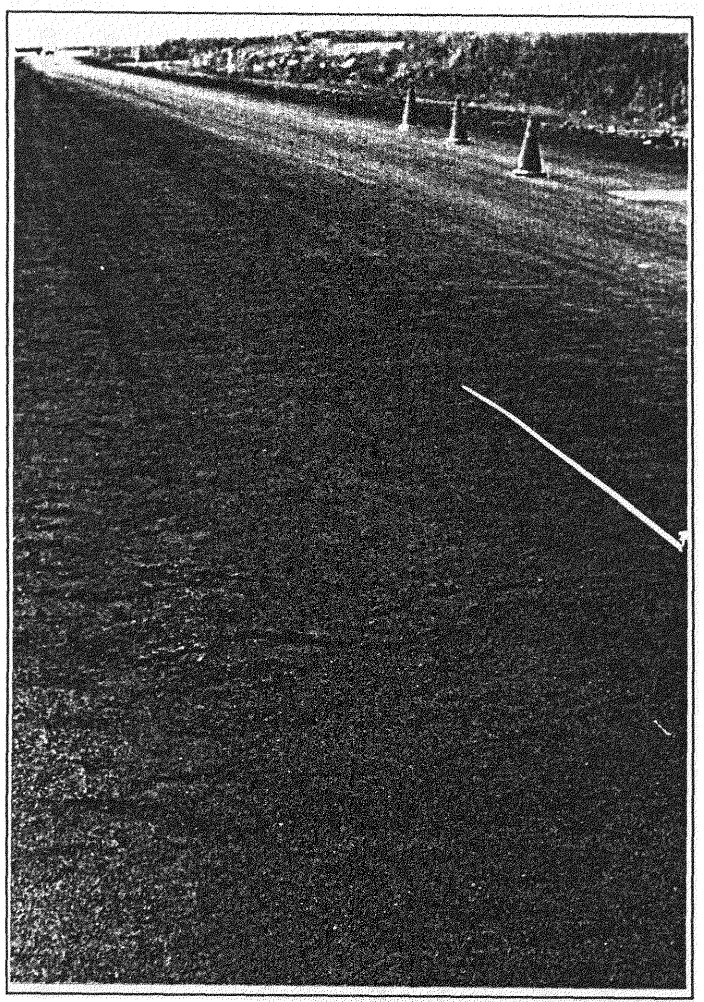


Figure 9.7 General View of Kriel Colliery Site 1, showing rutting and damage to wearing course.

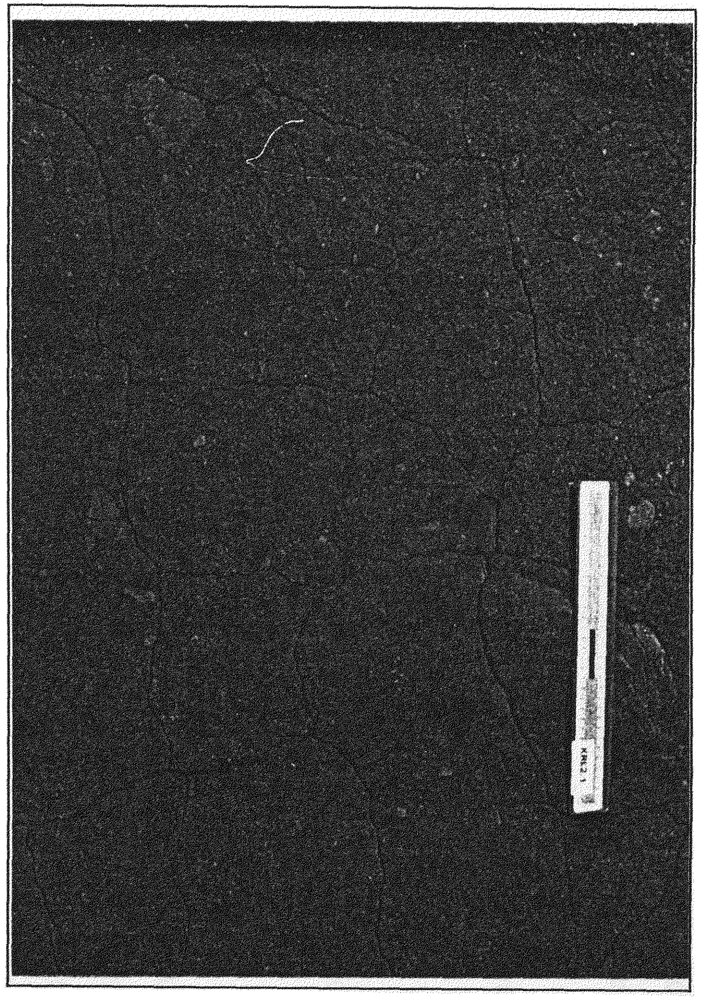


Figure 9.8 Crocodile cracking and large stones in wearing course, Kriel Colliery site 1.

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.

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 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

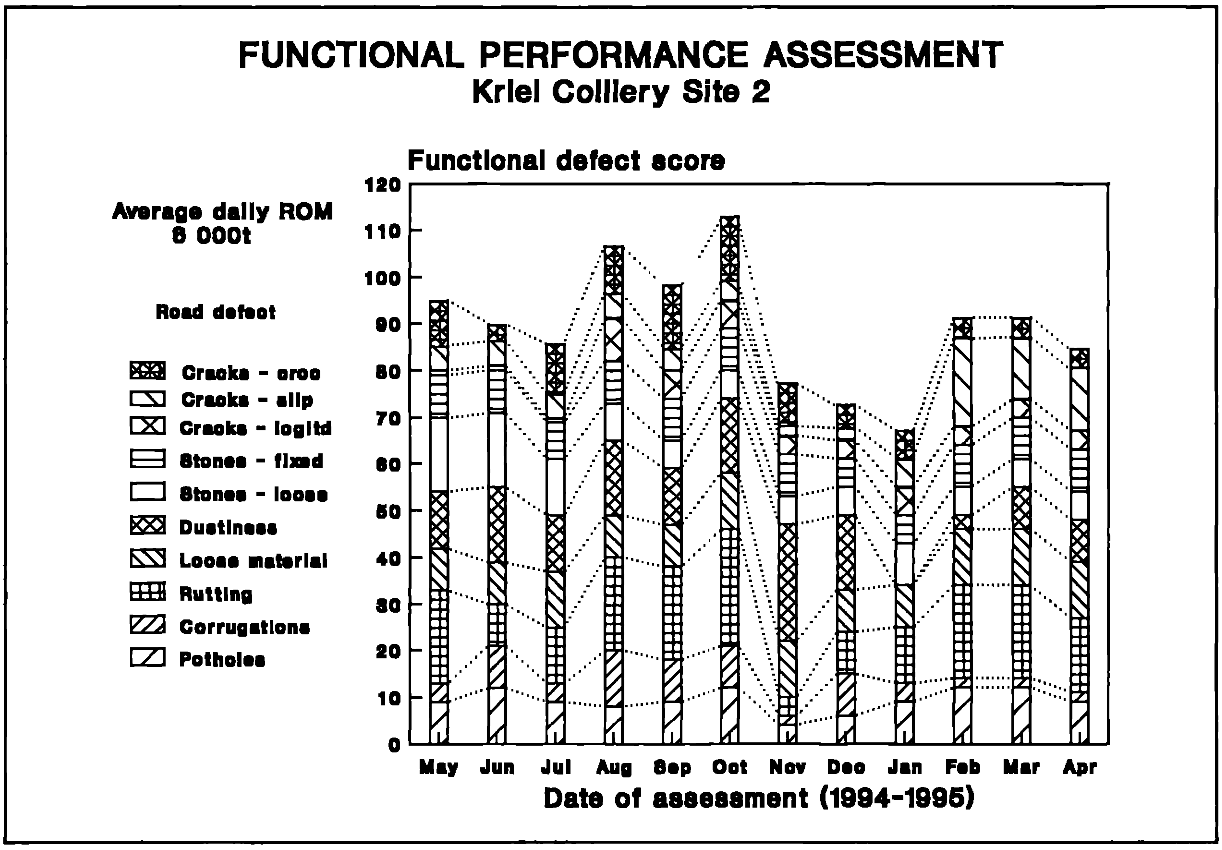


Figure 9.9 Functional Performance Assessment, Kriel Colliery Site 2.

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.

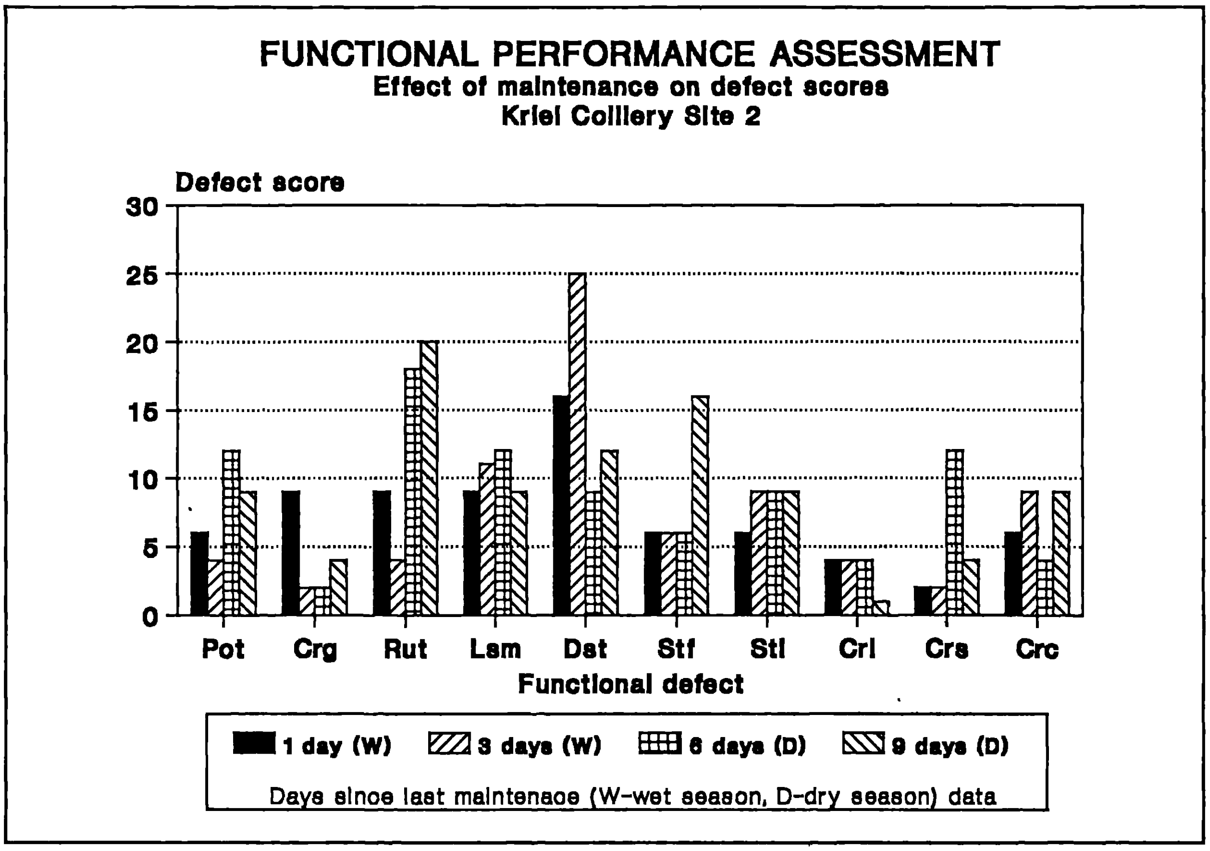


Figure 9.10 Effect of time since last maintenance on defect scores, Kriel Colliery site 2.

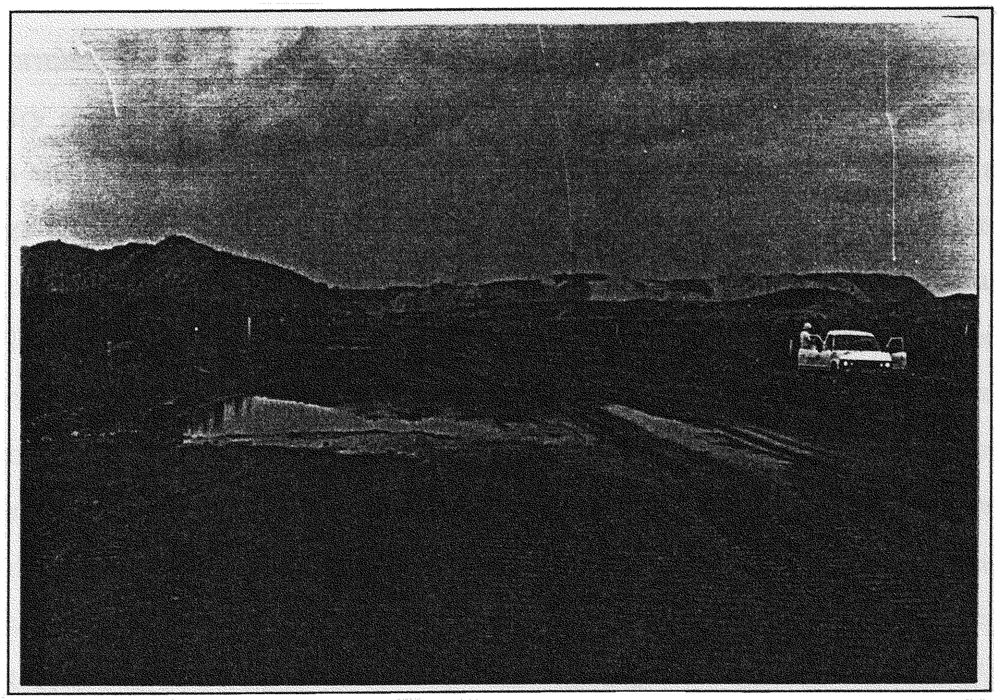


Figure 9.11 General View of Kriel Colliery Site 2.

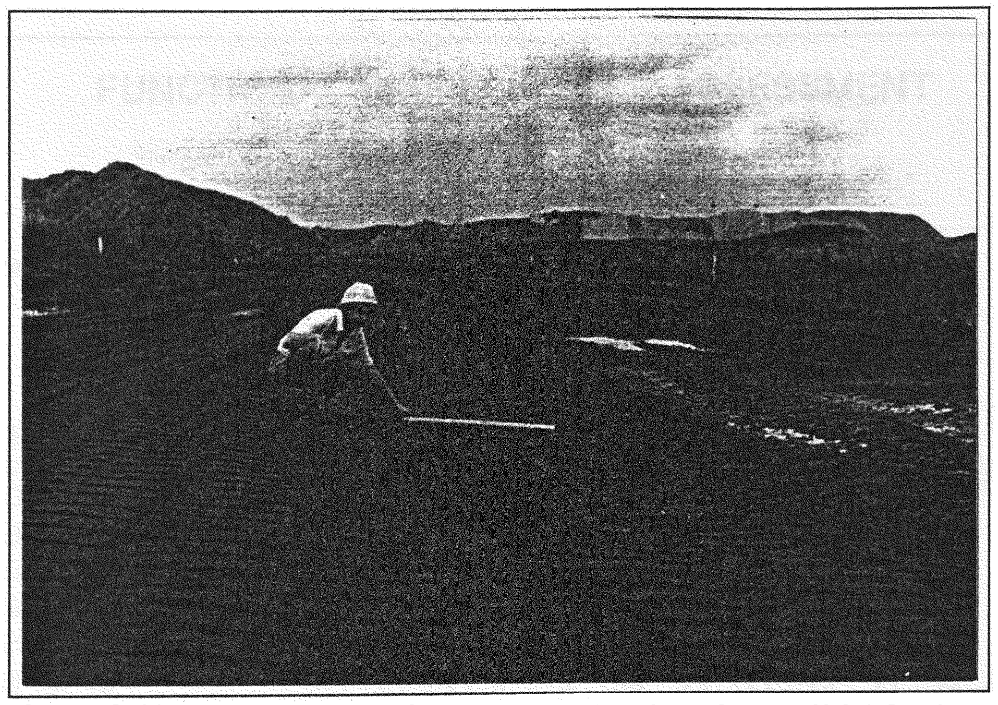


Figure 9.12 Damage to wearing course, laden side of road, Kriel Colliery Site 2.

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.

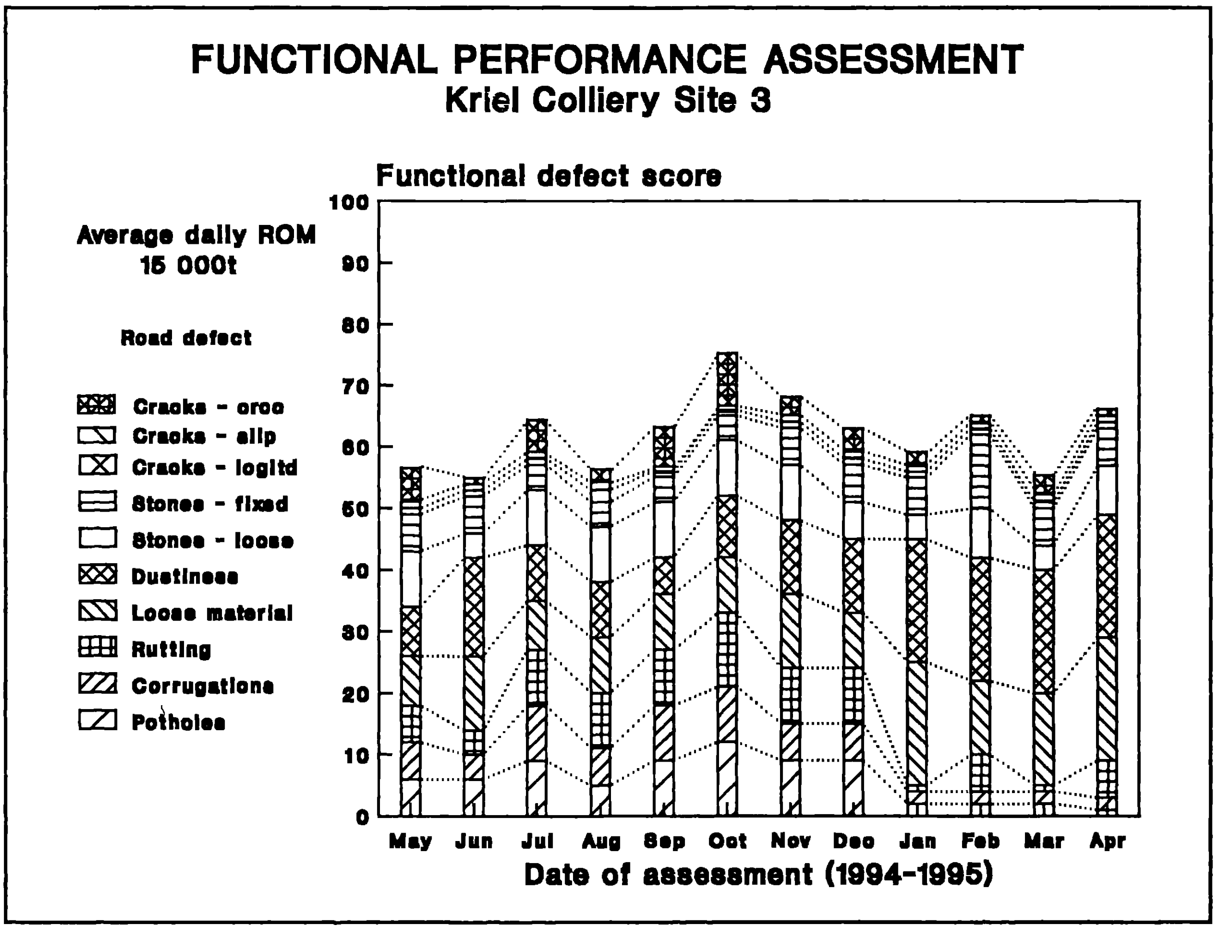


Figure 9.13 Functional Performance Assessment, Kriel Colliery Site 3

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.

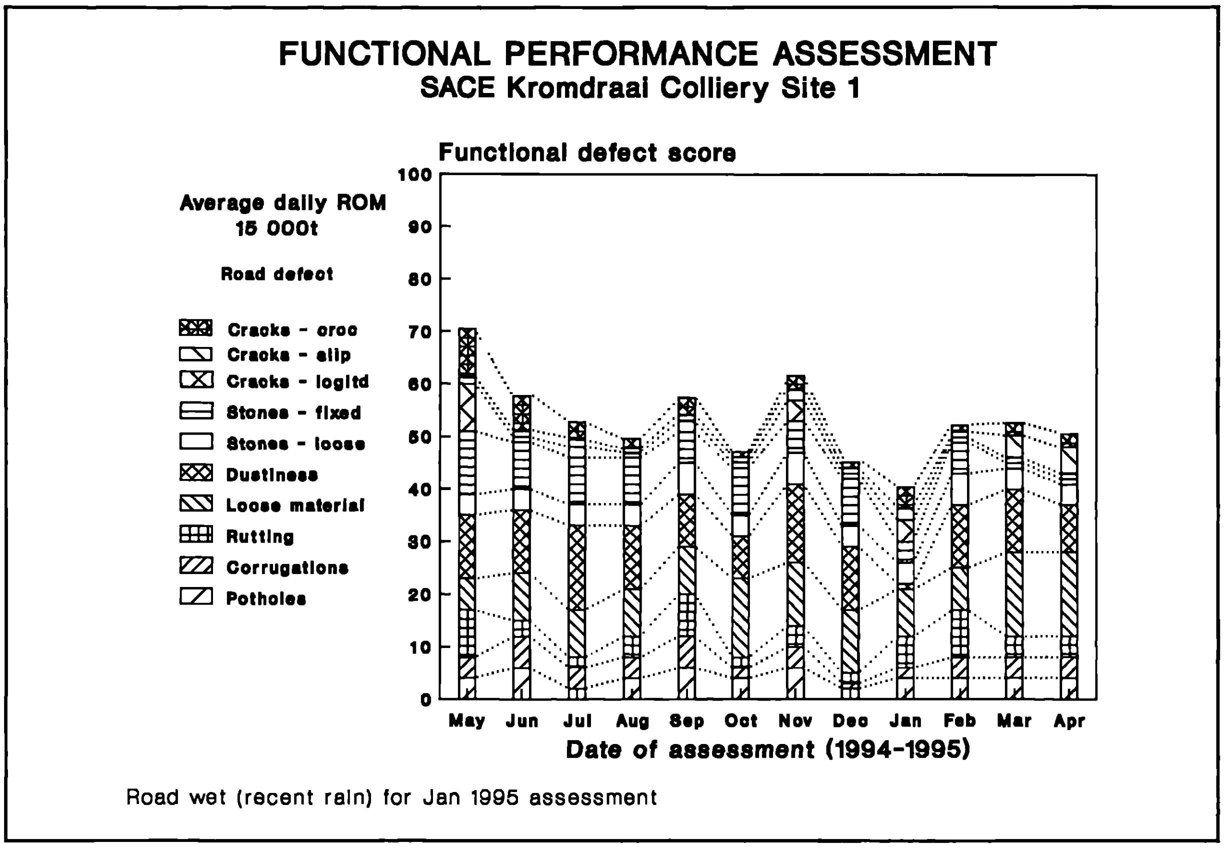
The wearing course material is sourced on the mine and is as such similar for all three sites. A G7 classification (following CSRA TRH14, 1985) is given to sites 1 and 2 whilst site 3 receives a G6 classification by virtue of higher California Bearing Ratio (CBR) values. Traffic levels encountered varied 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.

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 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.

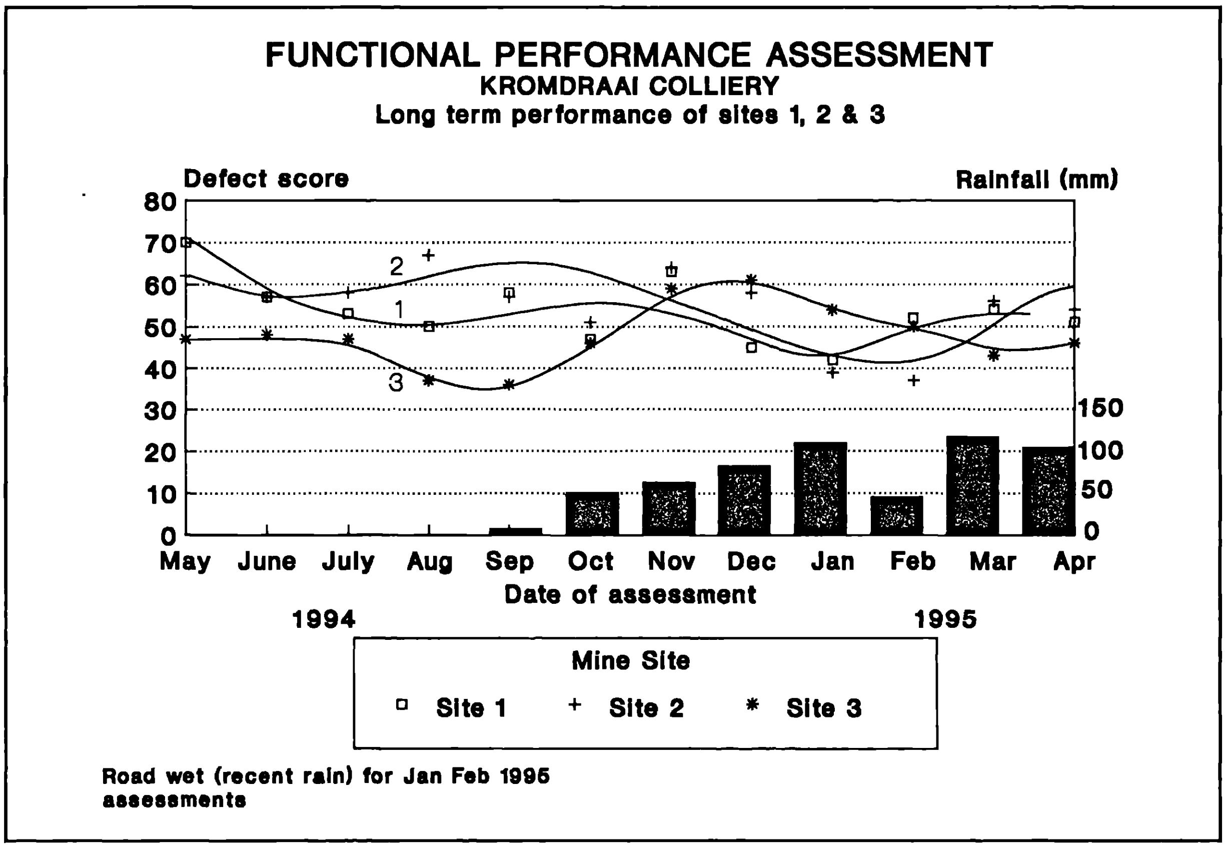
Figure 9.19 shows a general view of site 1 with the loaded side of the road on the LHS. Although the site is slightly on grade (1,7%), no significant erosion of the wearing course



FUNCTIONAL PERFORMANCE ASSESSMENT
SACE Kromdraai Colliery Site 1

Road wet (recent rain) for Jan 1995 assessment

Figure 9.15 Functional Performance Assessment - Kromdraai Mine Site 1.



FUNCTIONAL PERFORMANCE ASSESSMENT
KROMDRAAI COLLIERY
Long term performance of sites 1, 2 & 3

Road wet (recent rain) for Jan Feb 1995 assessments

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

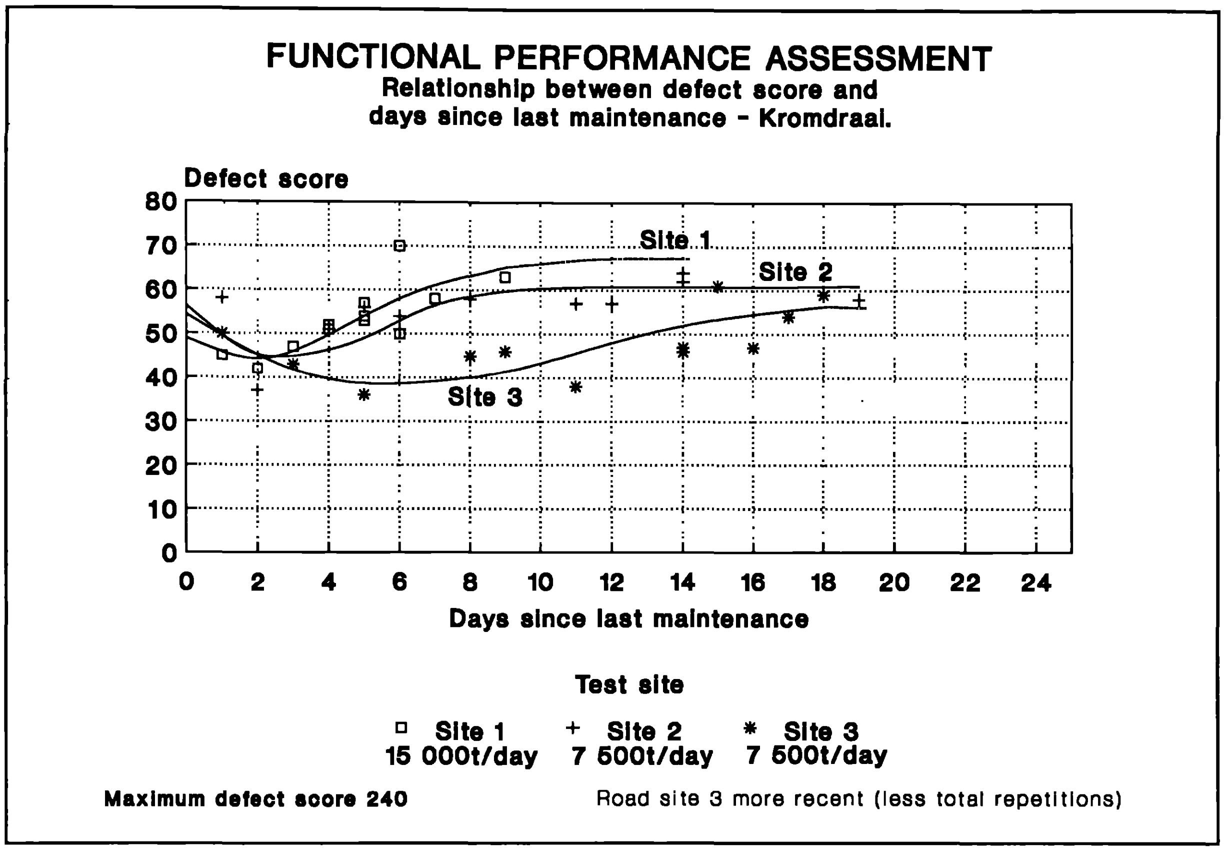


Figure 9.17 Effect of Maintenance on Defect Score - Kromdraai Colliery Sites 1, 2 and 3.

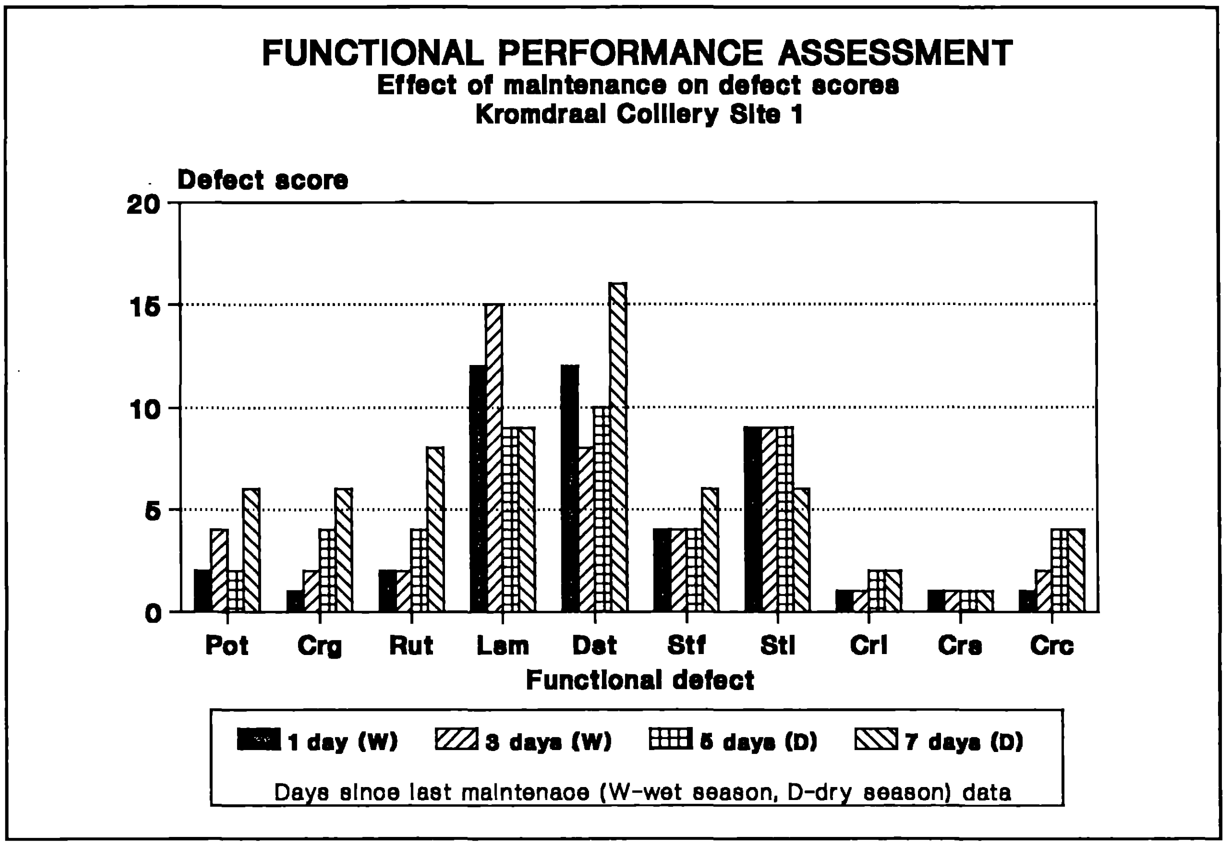


Figure 9.18 Effect of time since last maintenance on defect scores, Kromdraai Colliery site 1.

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

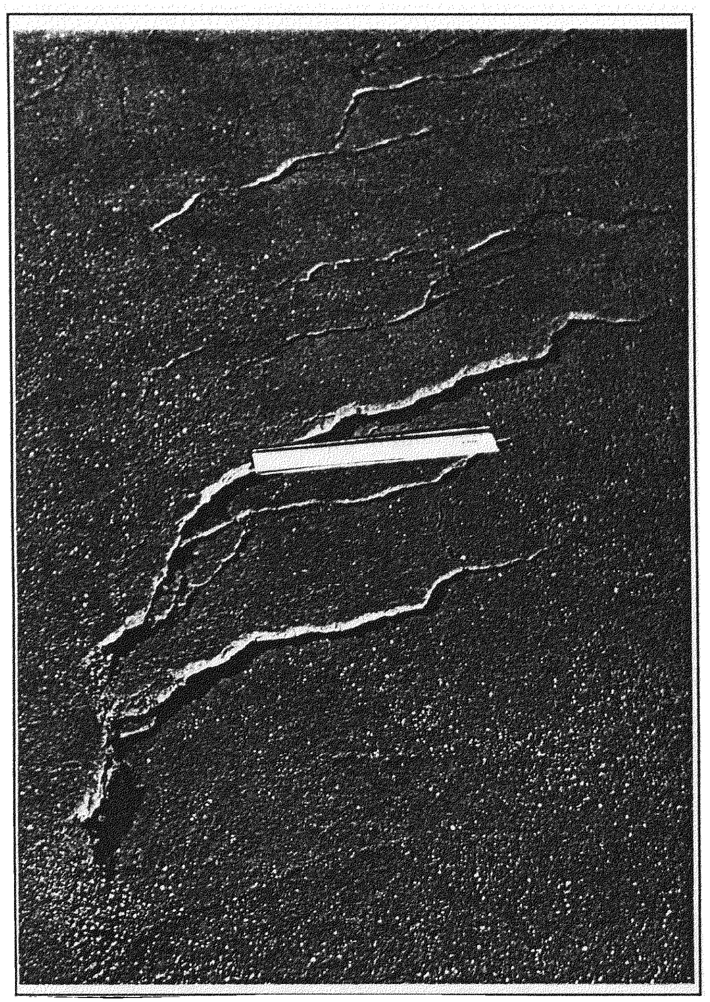


Figure 9.20 Cracking and pushing out of wearing course in centre of road, Kromdraai Colliery Site 1.

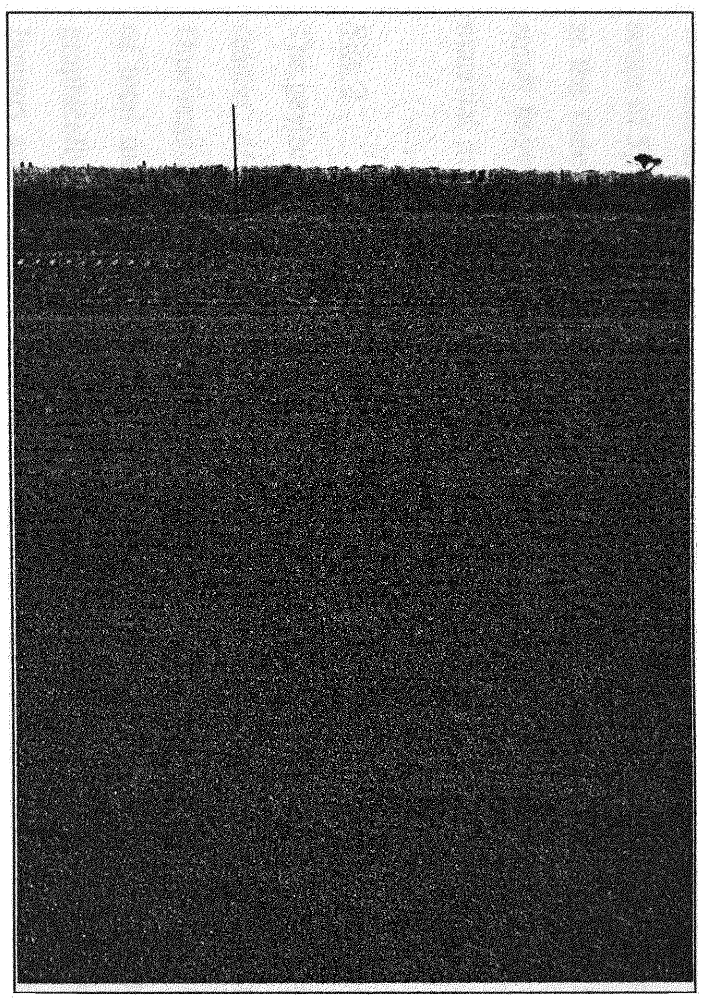


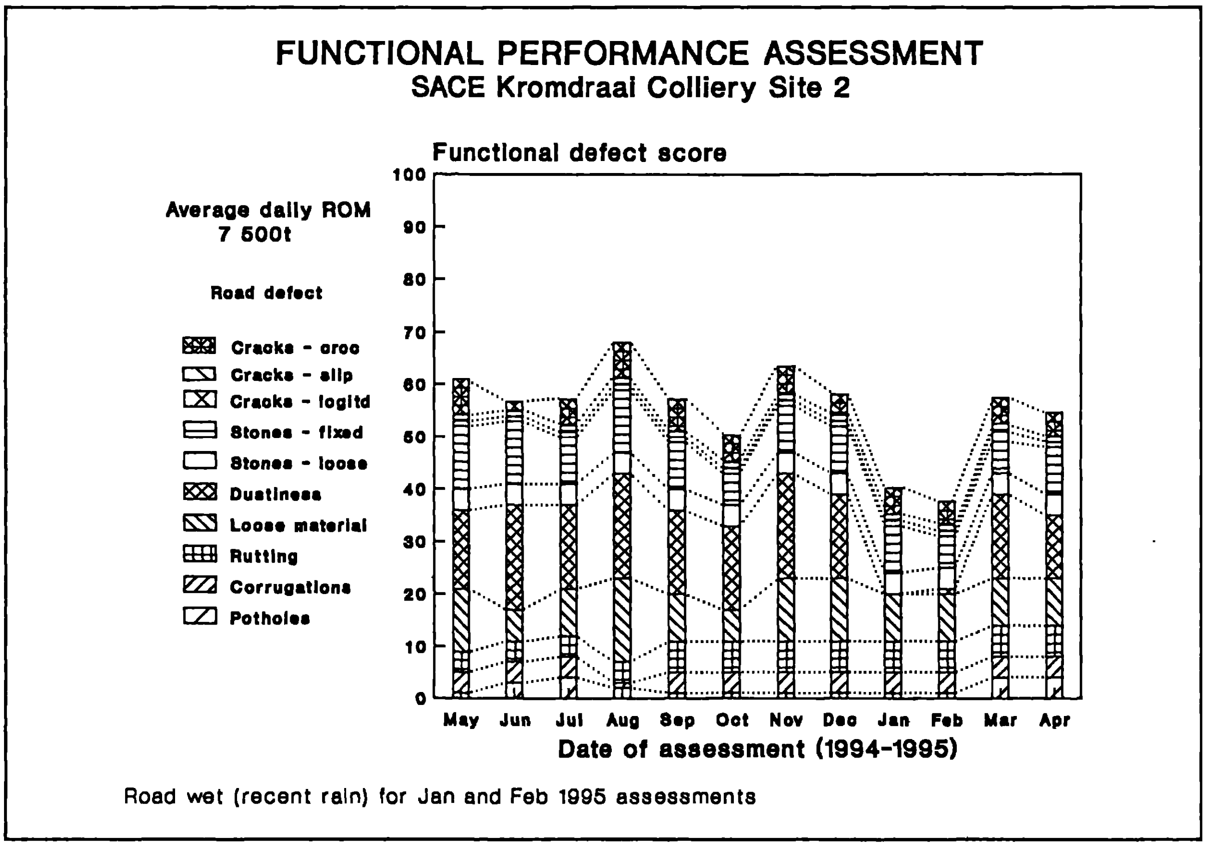
Figure 9.21 View across haul road at Kromdraai Colliery site 1 showing location of defect in centre of road.

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



Road wet (recent rain) for Jan and Feb 1995 assessments

Figure 9.22 Functional Performance Assessment - SACE Kromdraai Colliery site 2

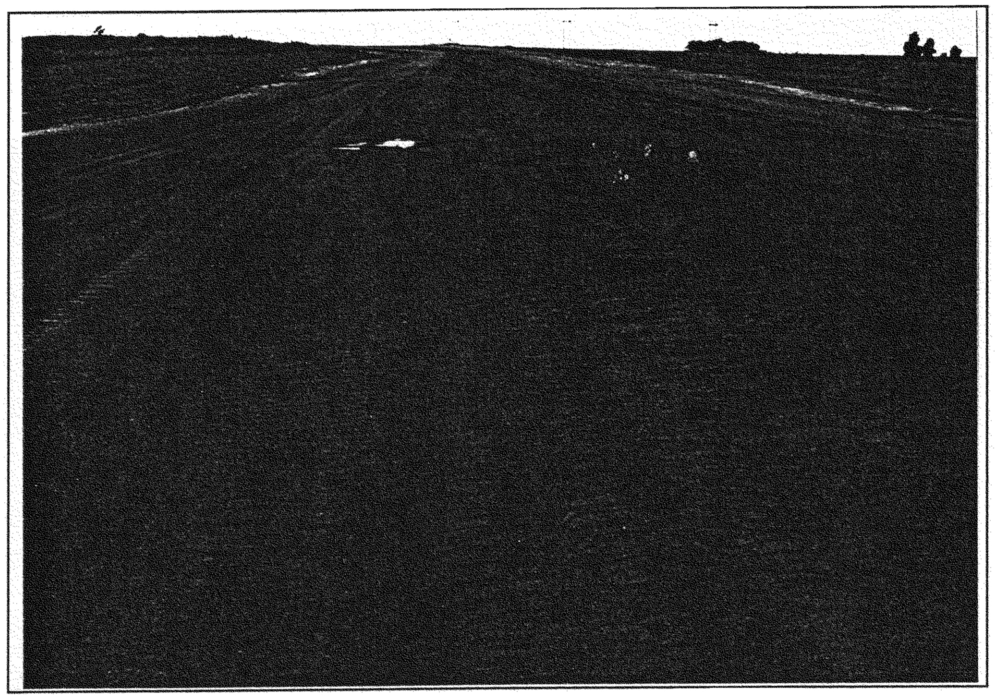


Figure 9.23 General View of SACE Kromdraai Site 2 (laden side of road on LHS).

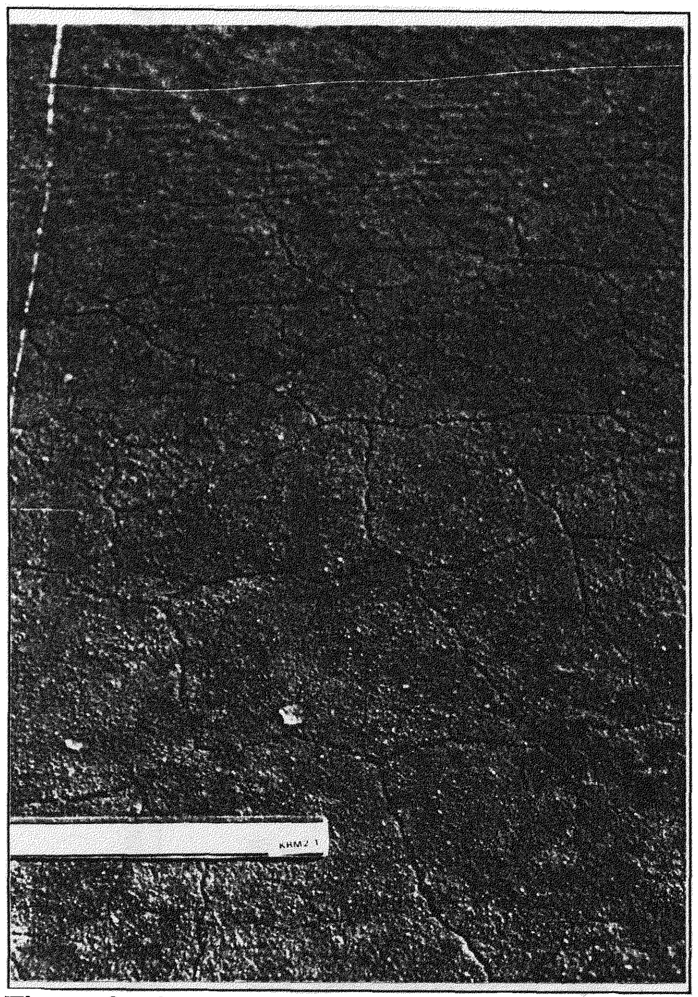


Figure 9.24 Typical crocodile cracking defect at SACE Kromdraai Colliery site 2.

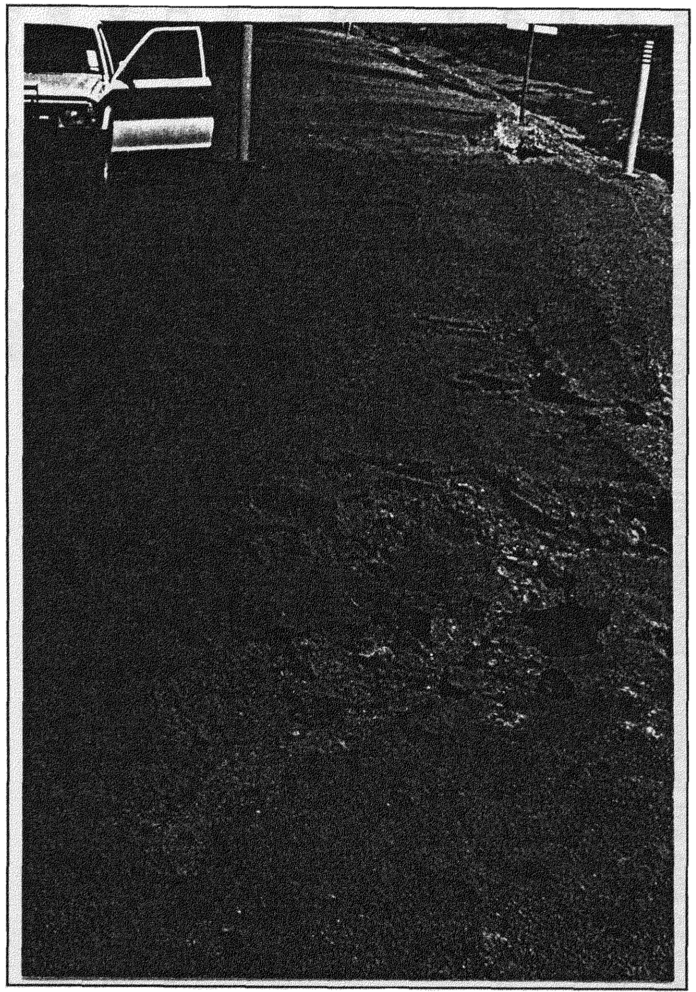
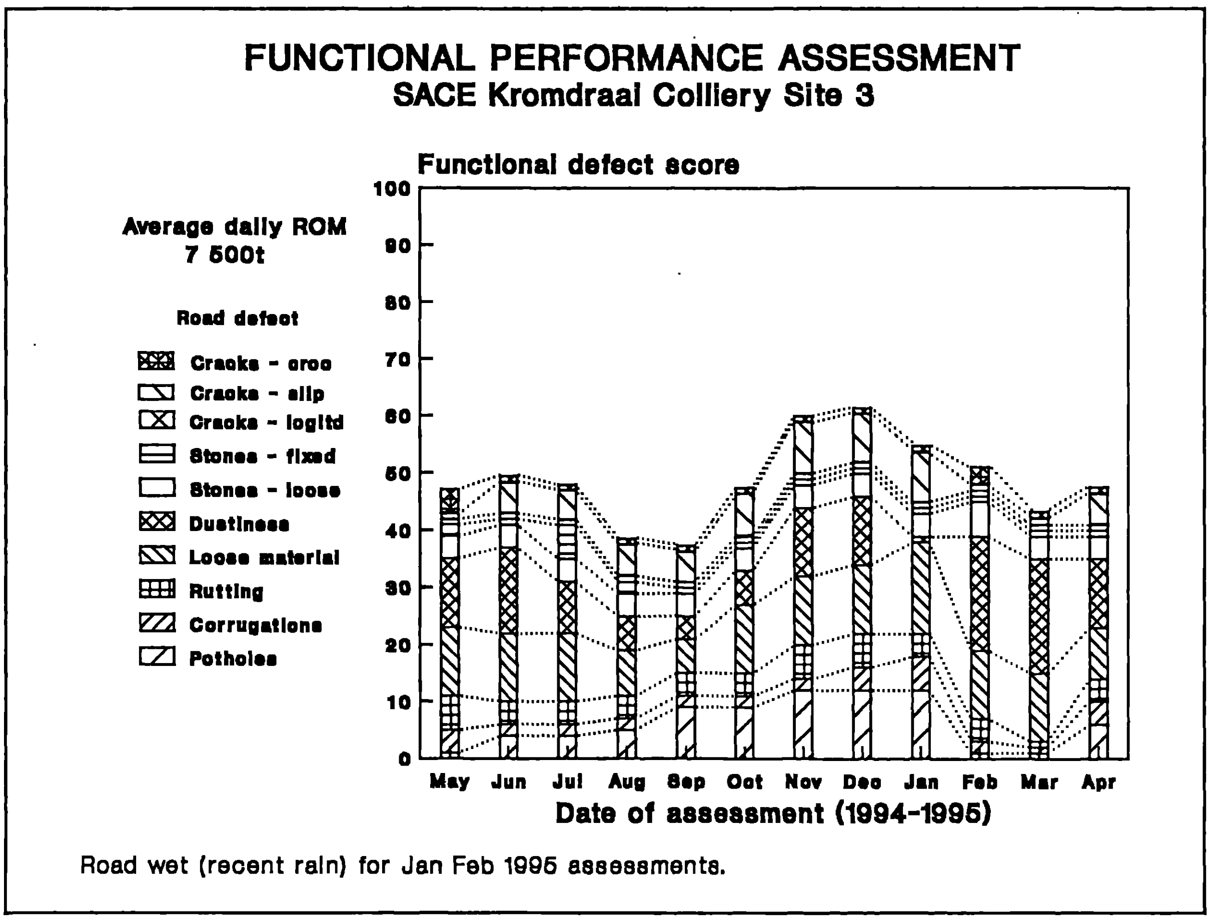


Figure 9.25 Erosion of edge of road coincident with road valley and locally excessive crossfall, SACE Kromdraai Colliery site 2.

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.



Road wet (recent rain) for Jan Feb 1995 assessments.

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.

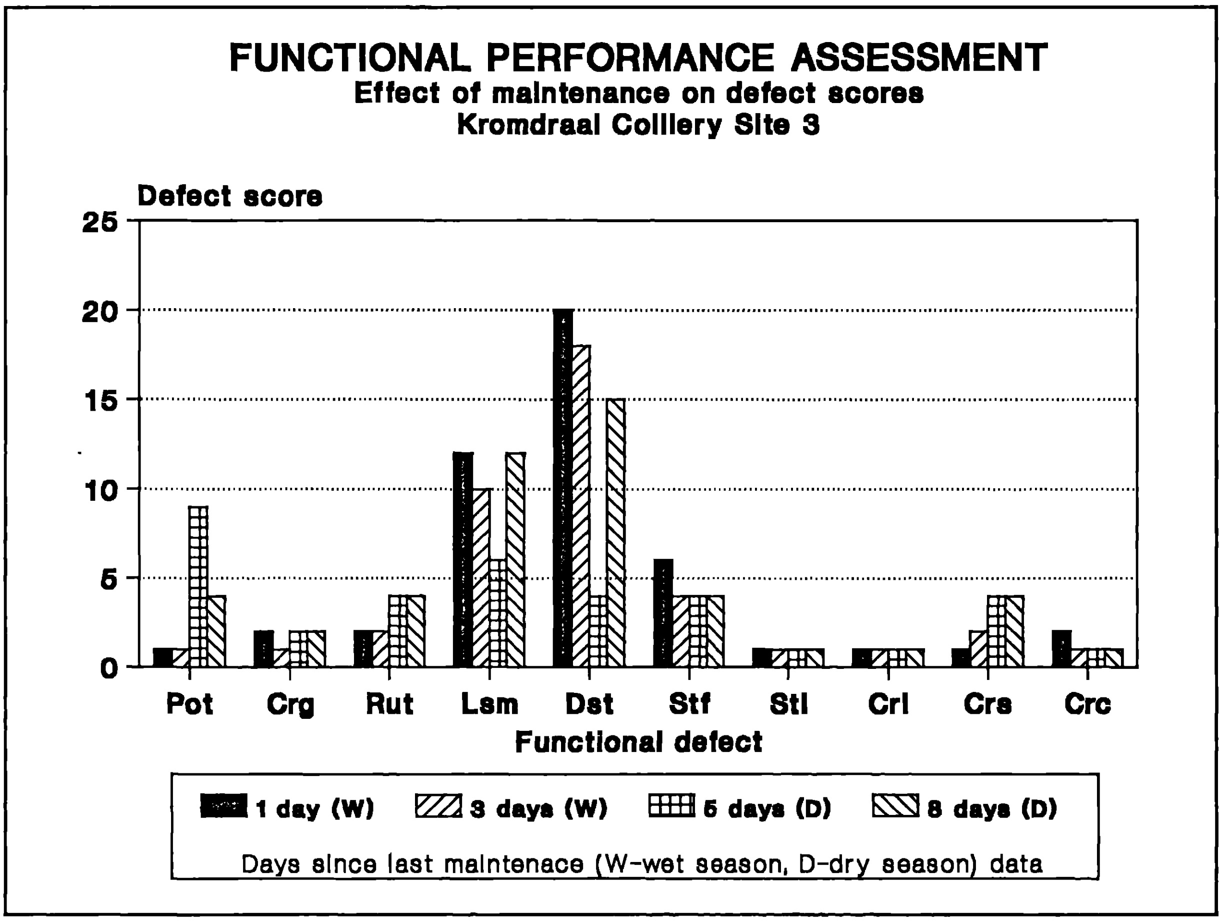


Figure 9.27 Effect of time since last maintenance on defect scores, Kromdraai Colliery site 3.

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.

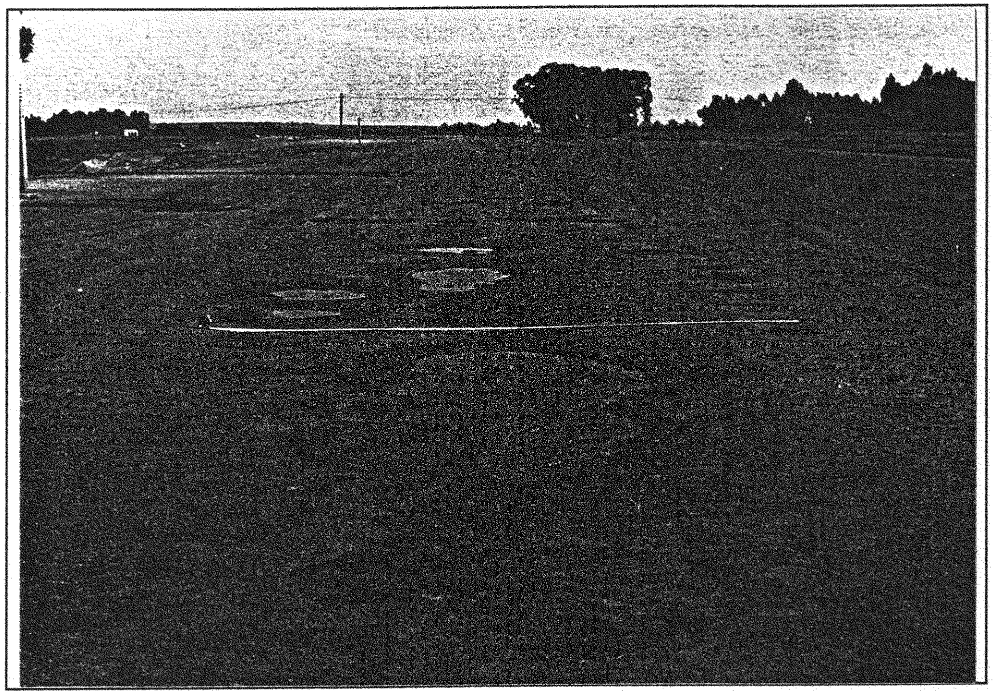


Figure 9.28 Potholing as a result of localised soft spot in newly constructed and trafficked site 3 road at SACE Kromdraai Colliery.

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".

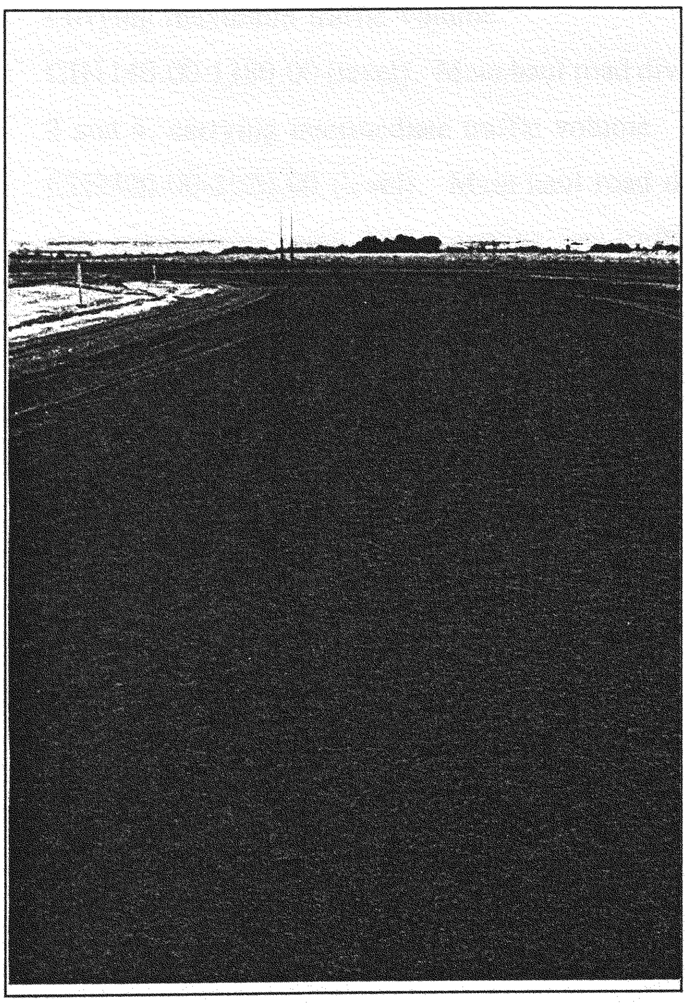


Figure 9.29 Churning of wearing course after recent rain, Kromdraai Colliery site 3 (laden side of road LHS)

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

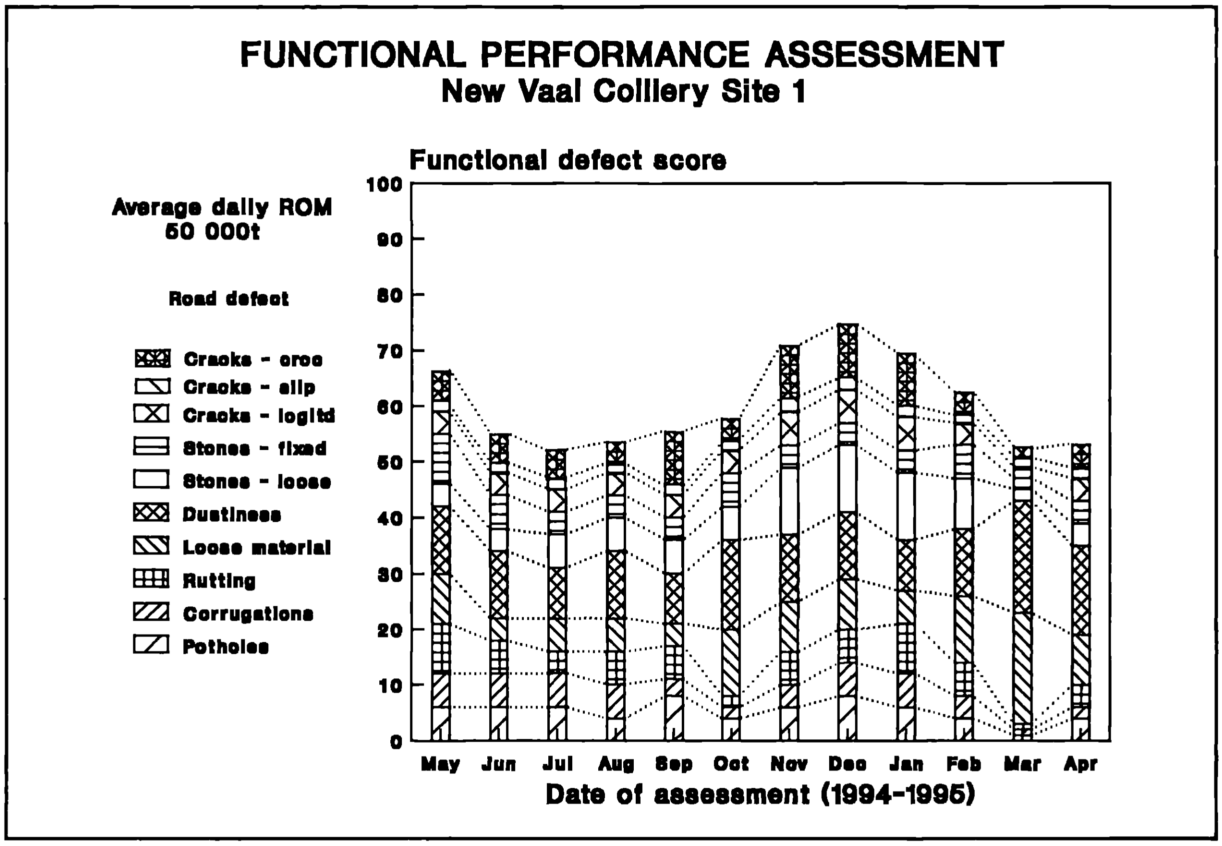


Figure 9.30 Functional Performance Assessment, New Vaal Colliery Site 1.

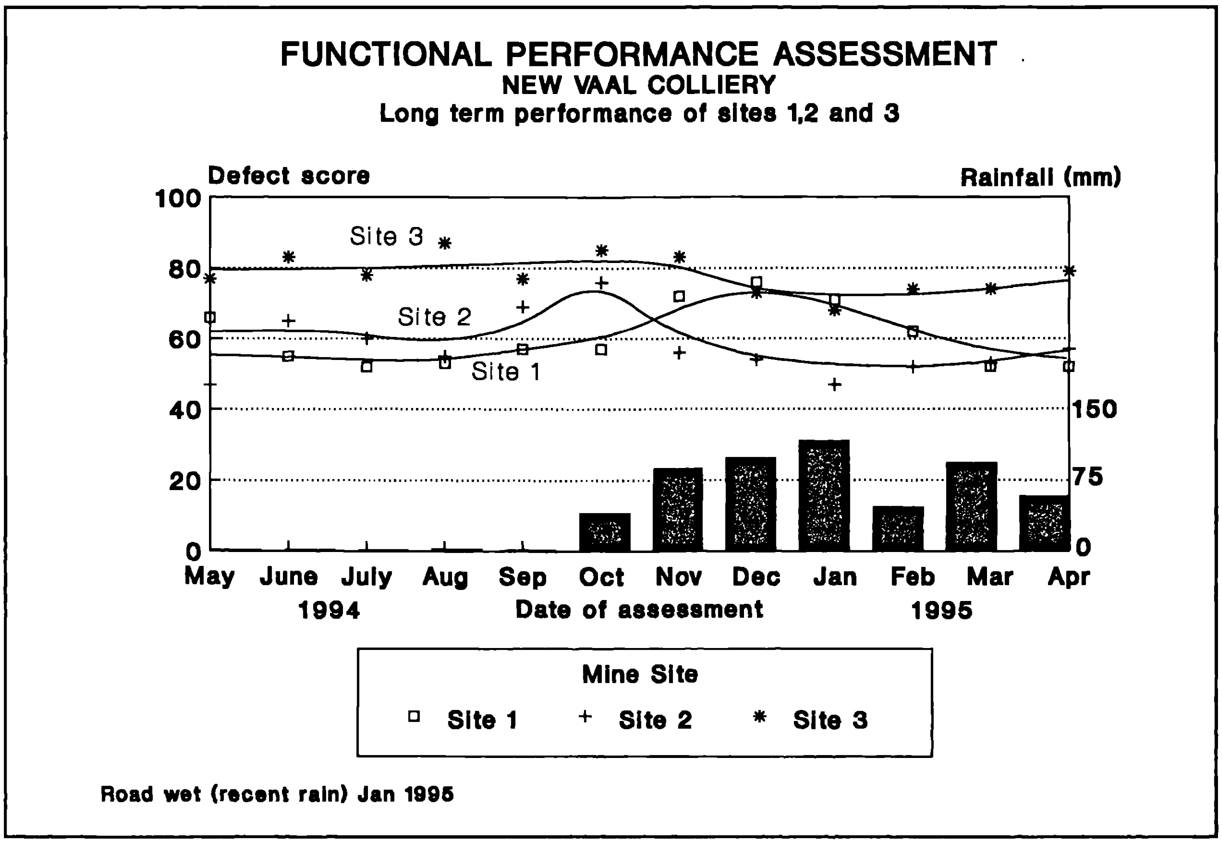


Figure 9.31 Long Term Performance Assessment of Sites 1, 2 and 3, New Vaal Colliery

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.

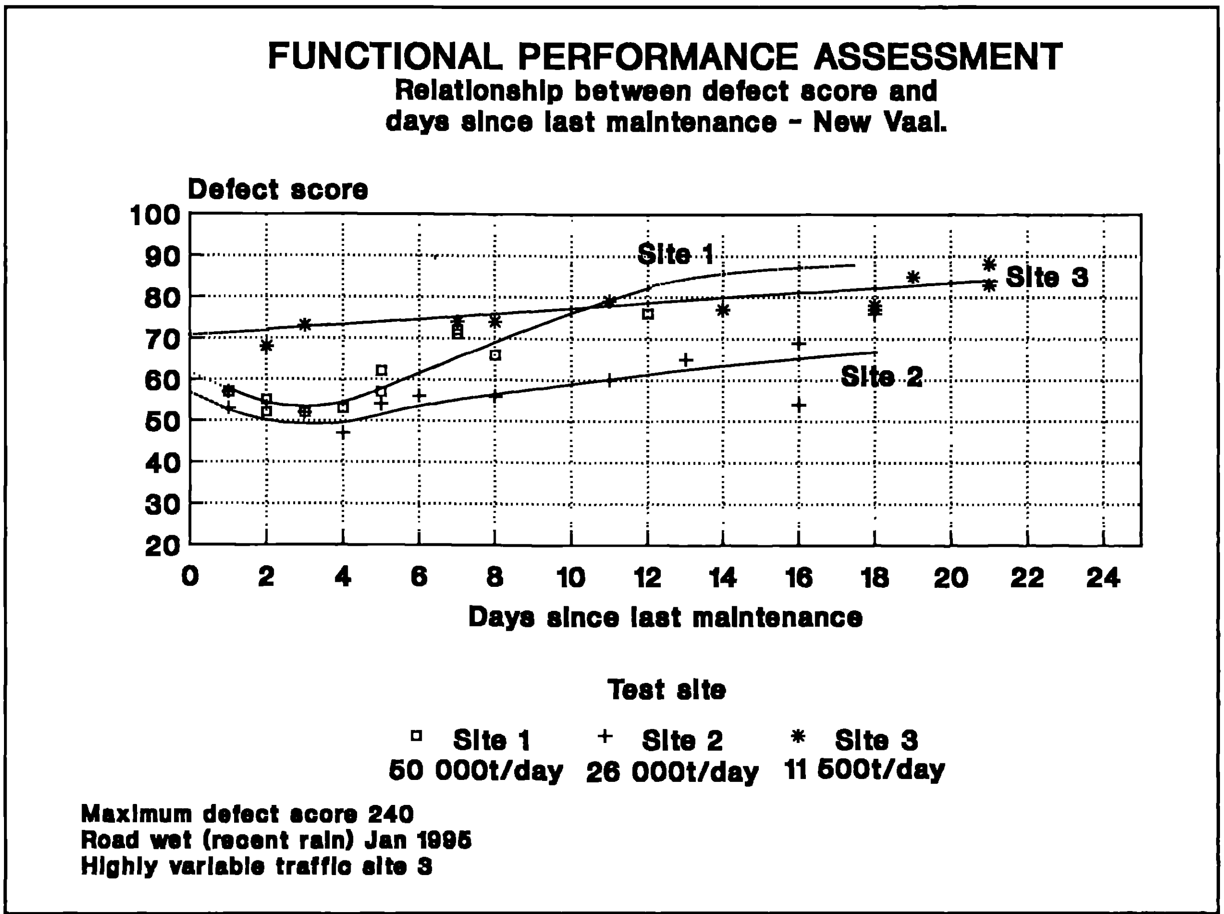


Figure 9.32 Effect of Maintenance on Defect Score - New Vaal Colliery Sites 1, 2 and 3.

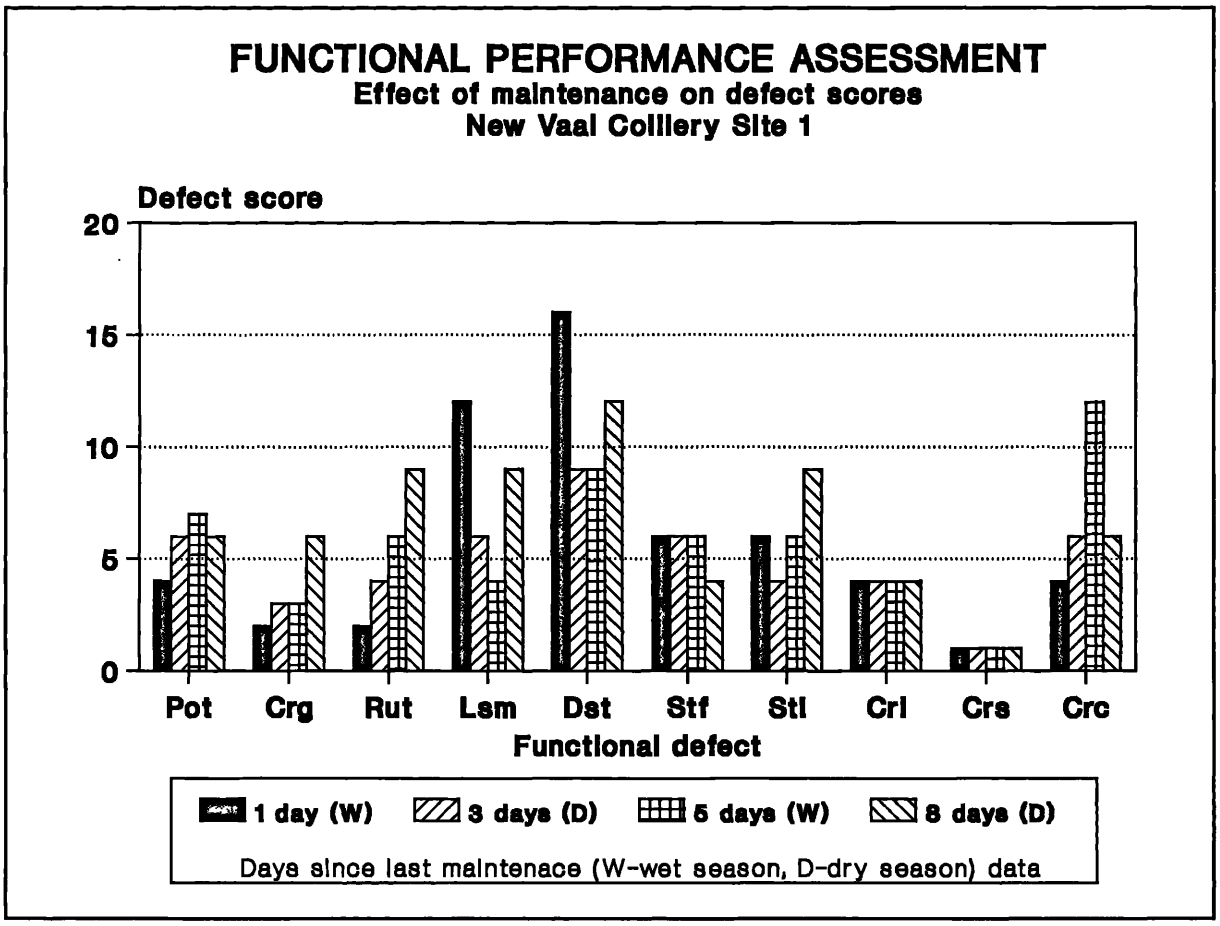


Figure 9.33 Effect of time since last maintenance on defect scores, New Vaal Colliery site 1.

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

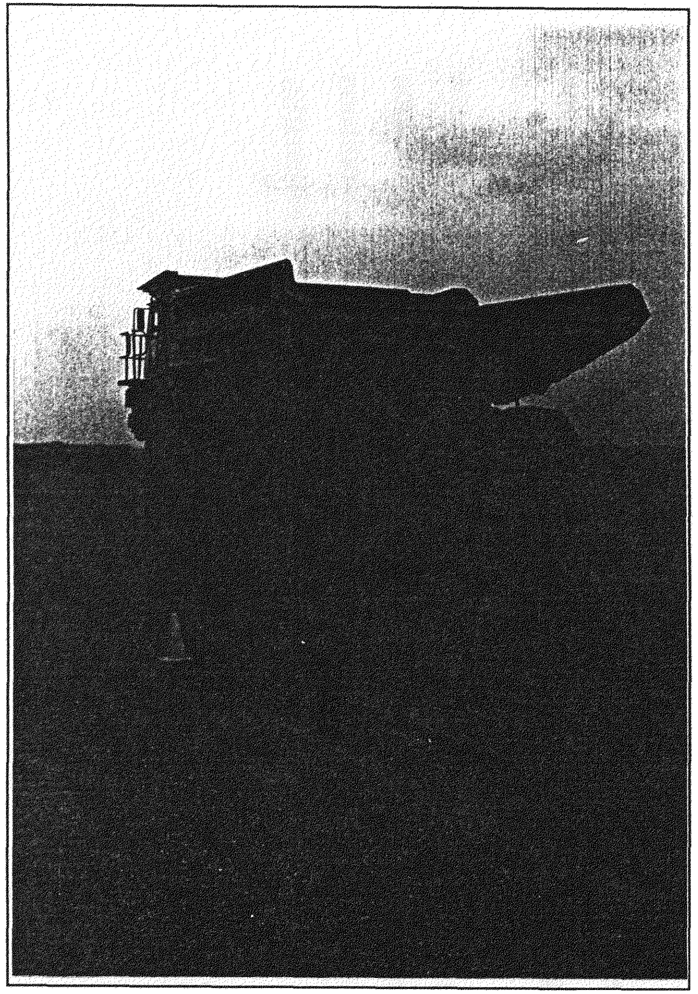


Figure 9.34 Haul Road Dust Defect (Dry Road), New Vaal Colliery Site 1

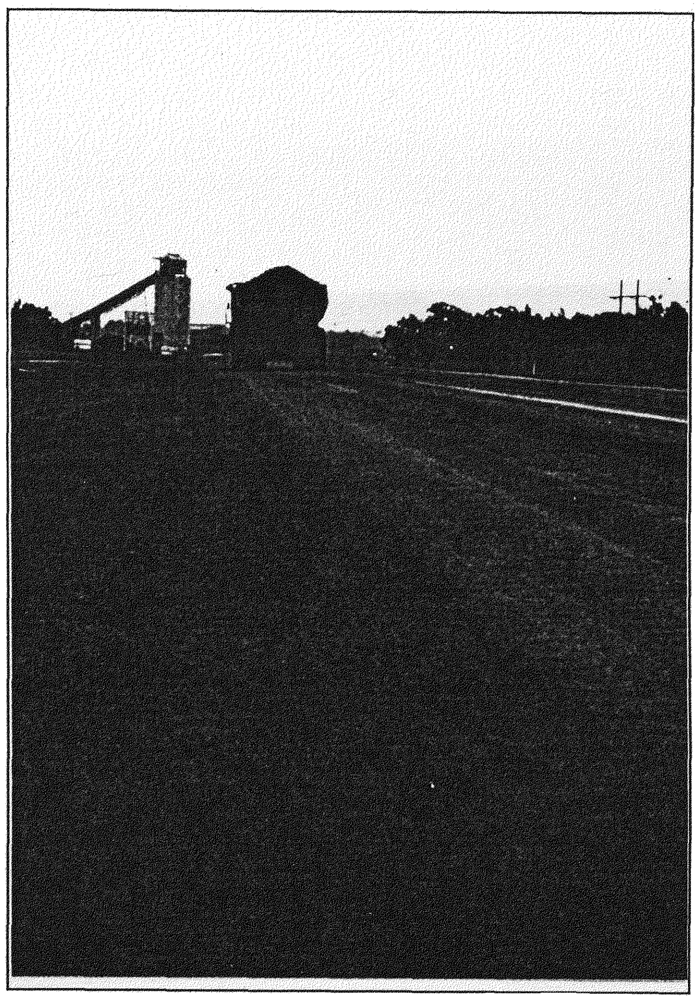


Figure 9.35 Dust Defect Conditions (wet road), New Vaal Colliery Site 1

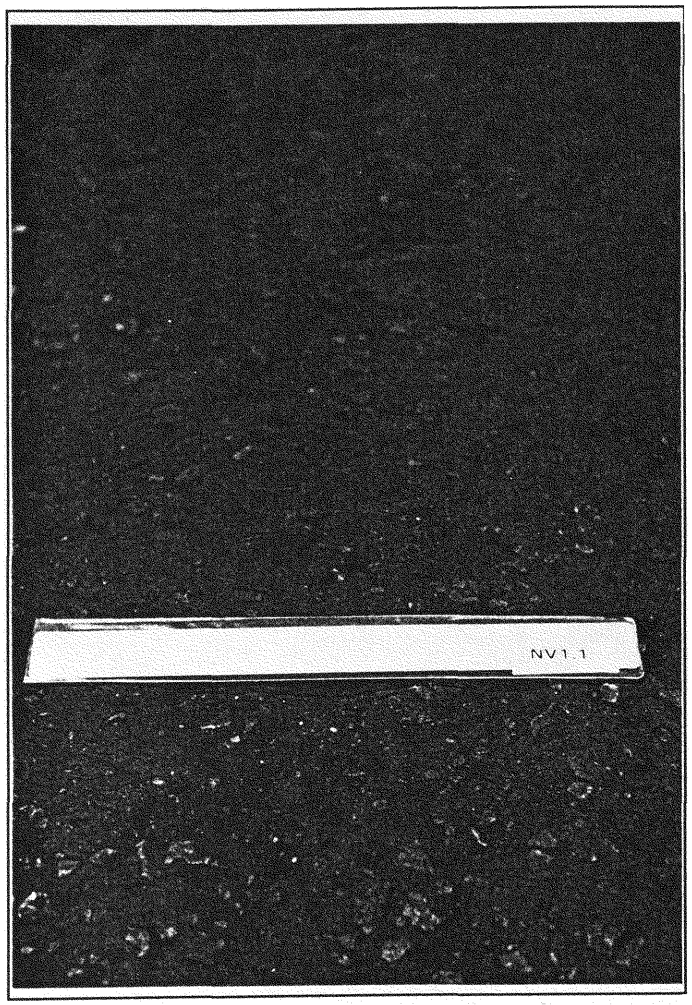


Figure 9.36 Pock Marks in Wearing Course as a Precursor to Larger Potholing (Figure 9.37), New Vaal Colliery Site 1.

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.

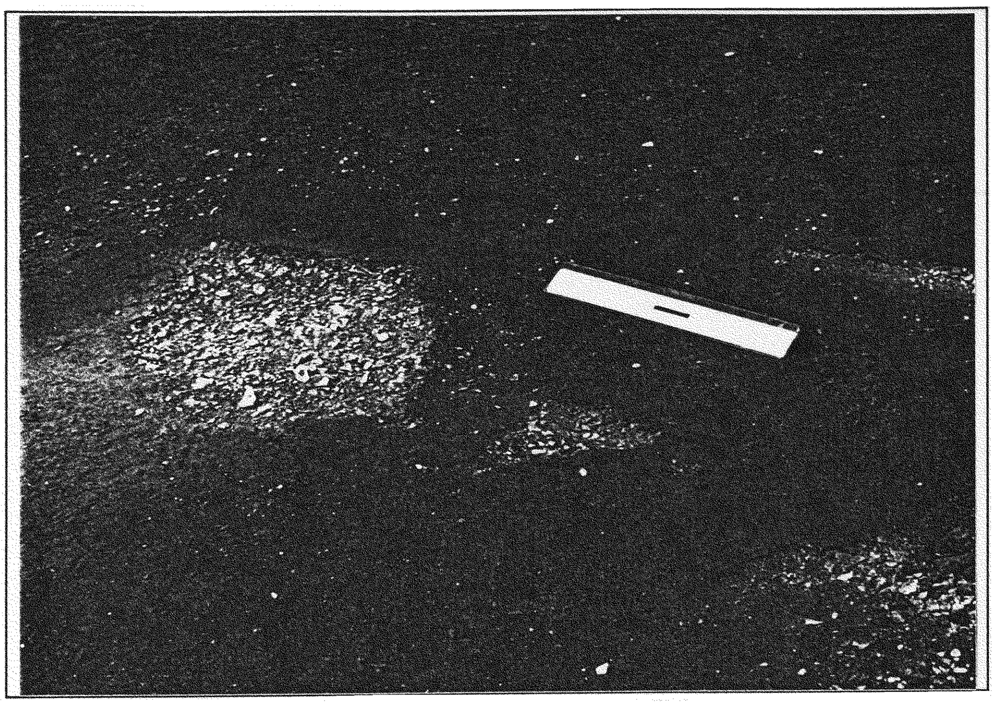


Figure 9.37 Pothole Formation, New Vaal Colliery Site 1.

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

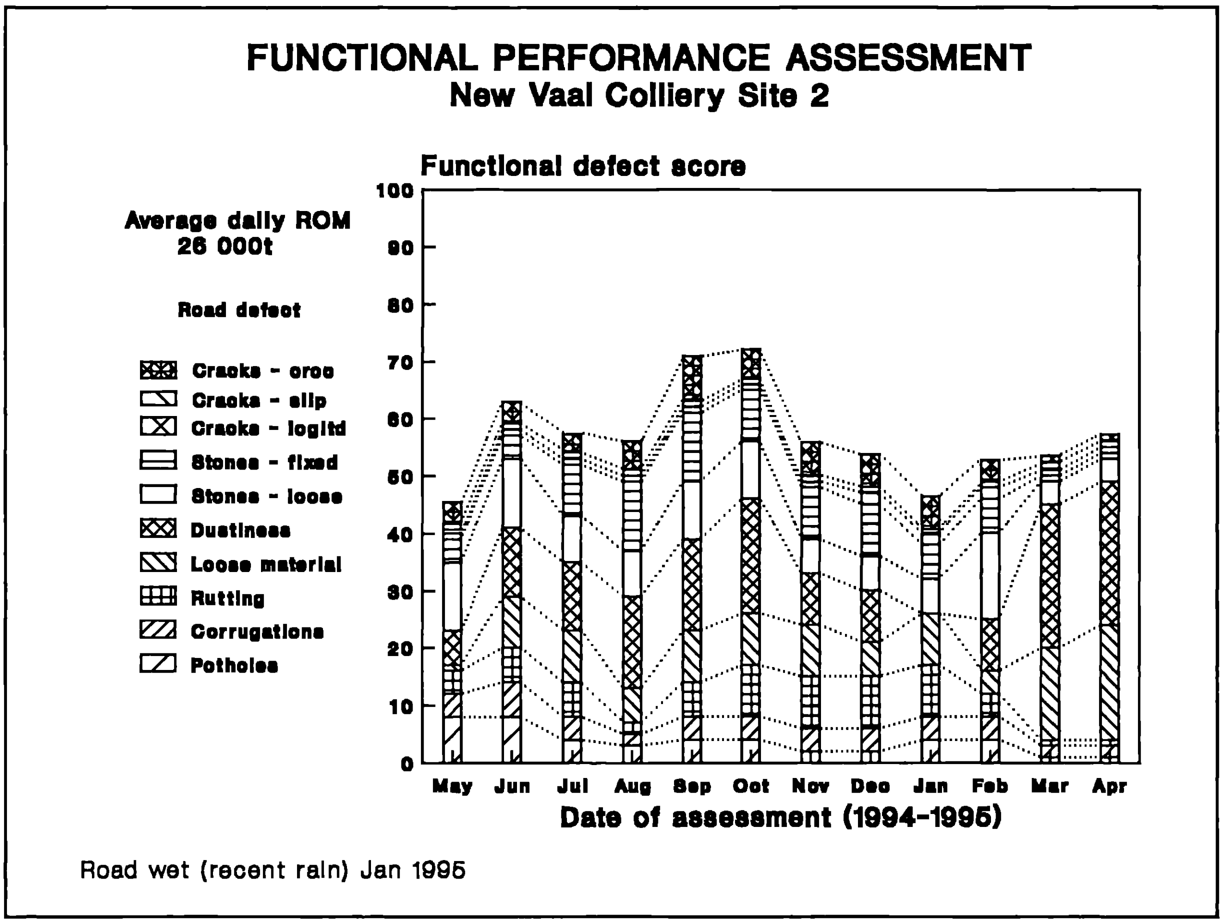


Figure 9.38 Functional Performance Assessment, New Vaal Colliery Site 2.

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

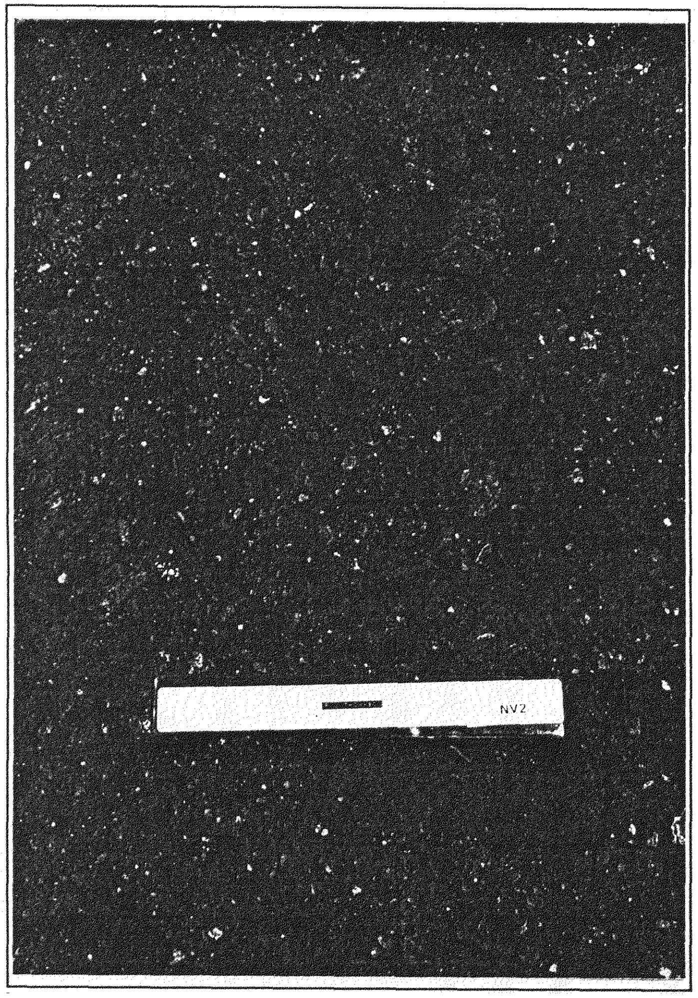


Figure 9.39 Stones fixed in wearing course, New Vaal Colliery site 2

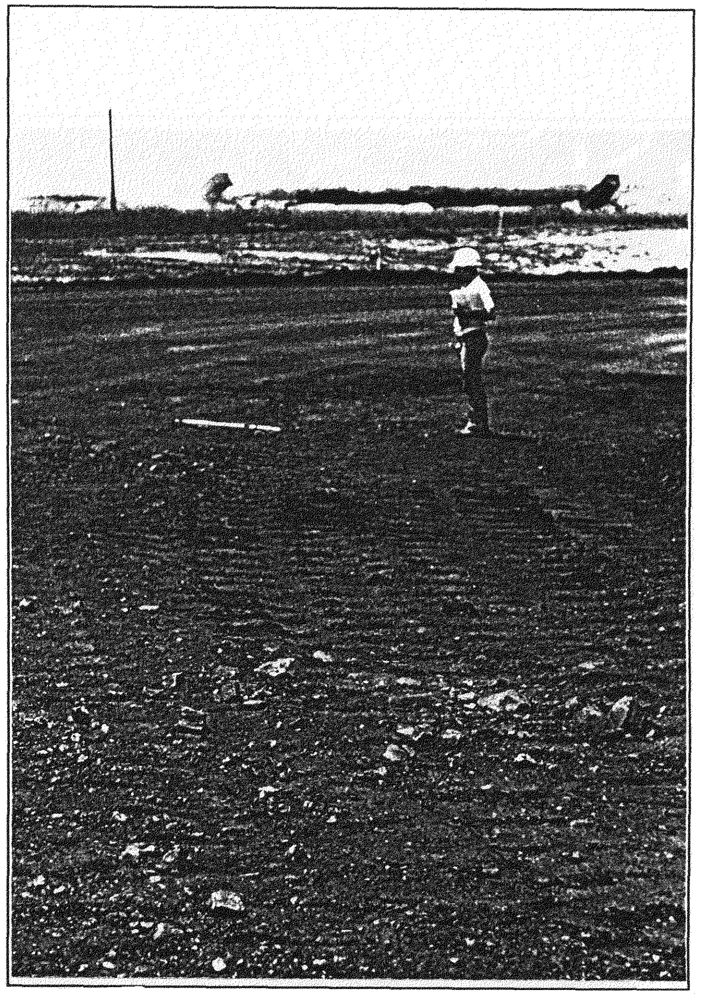


Figure 9.40 Typical damage to wearing course on bends, showing exposed stones, New Vaal Colliery Site 2.

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.

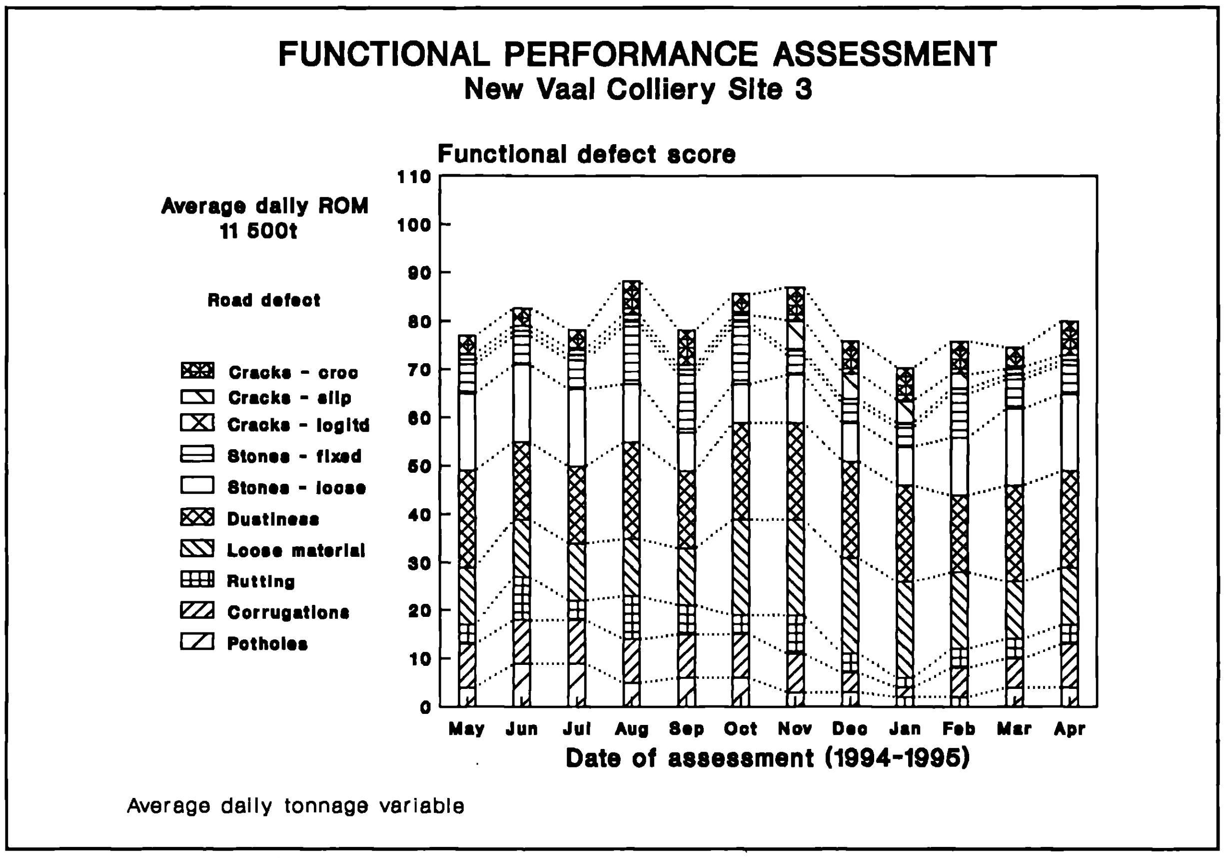


Figure 9.42 Functional Performance Assessment, New Vaal Colliery Site 3.

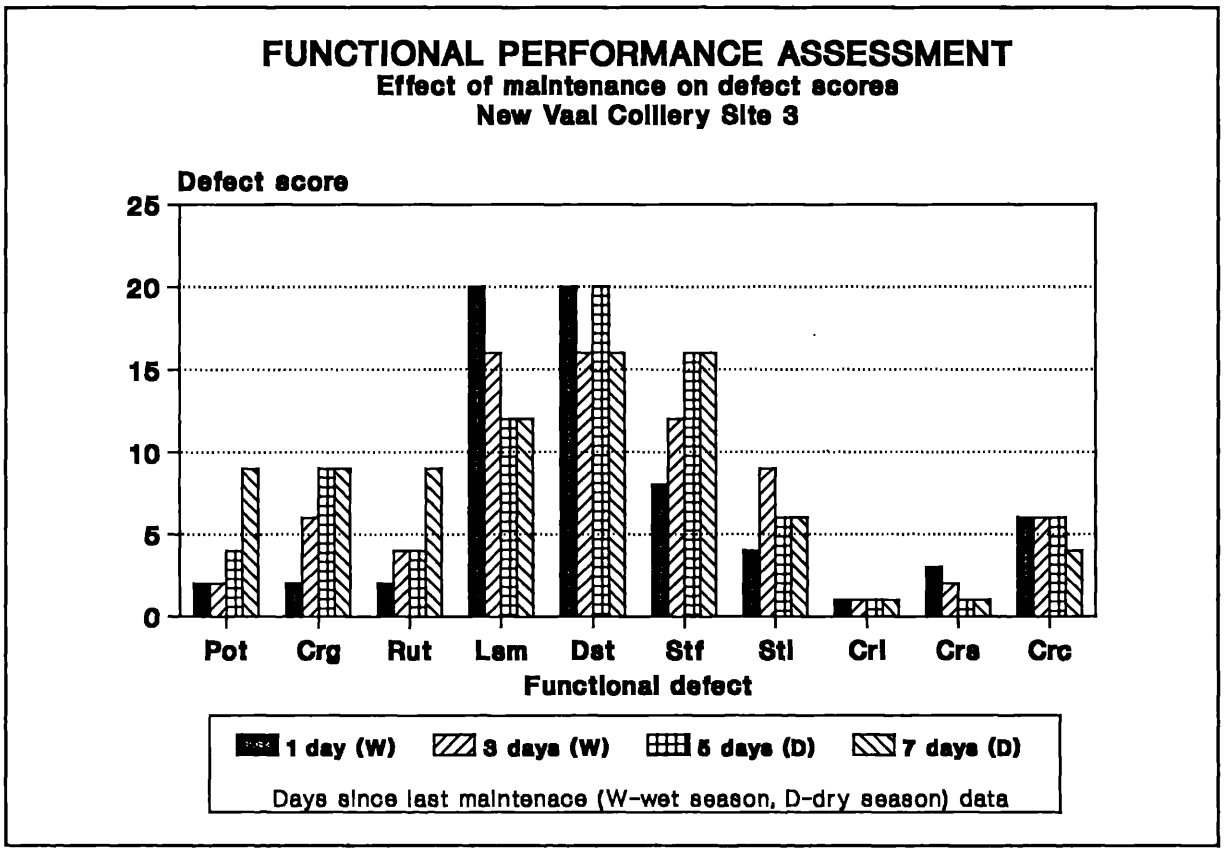


Figure 9.43 Effect of time since last maintenance on defect scores, New Vaal Colliery site 3.

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.

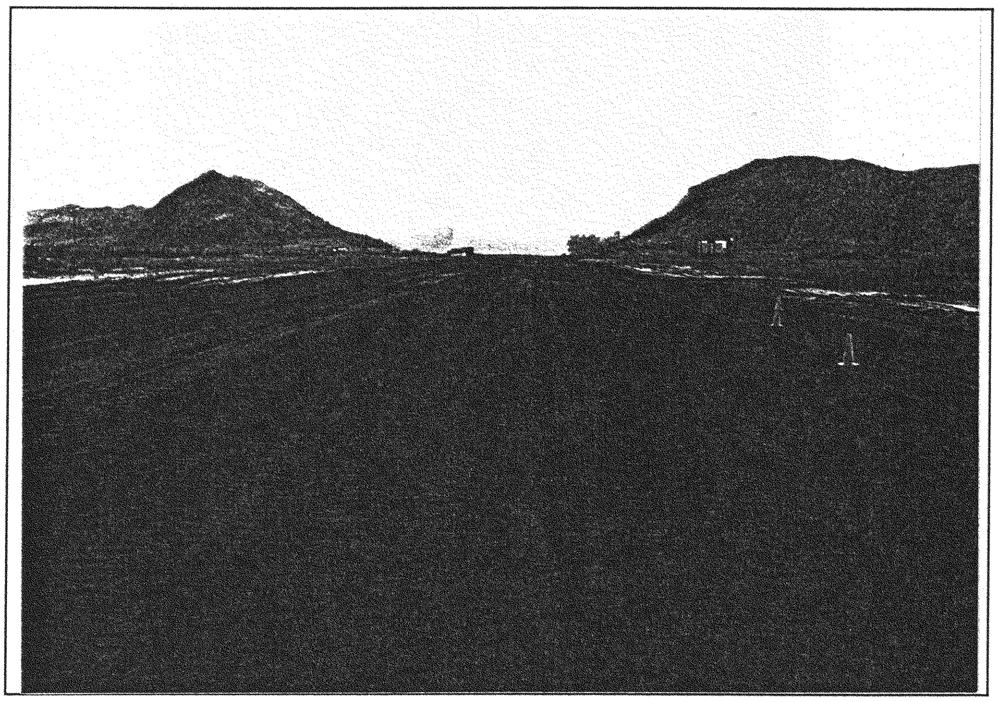


Figure 9.44 General view of New Vaal Colliery Site 3.

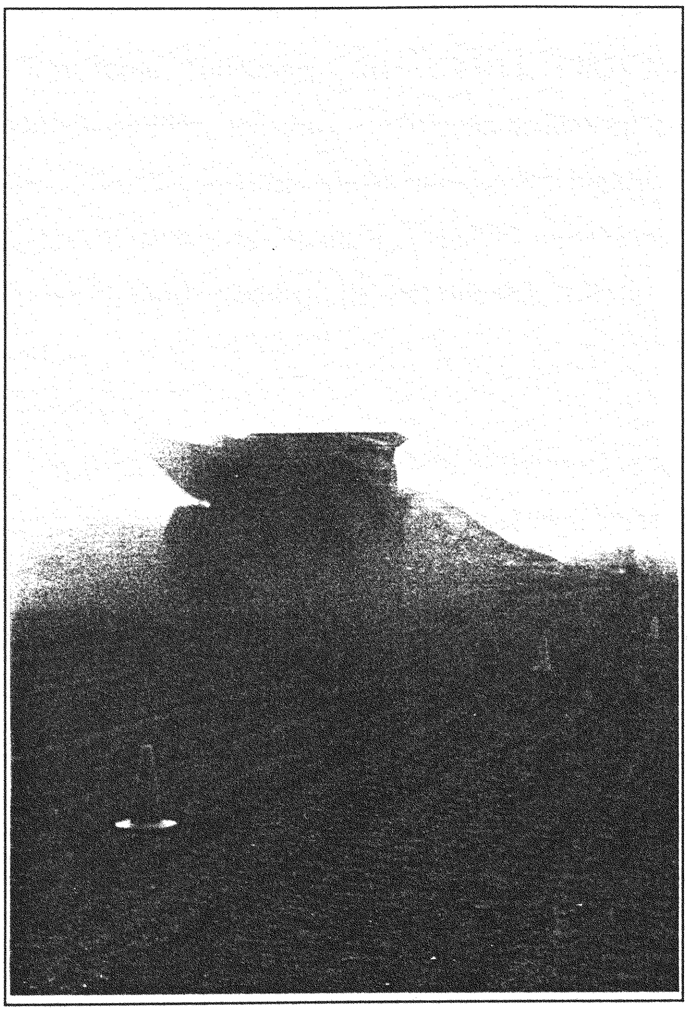


Figure 9.45 Dust defect (dry road) at New Vaal Colliery Site 3.

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

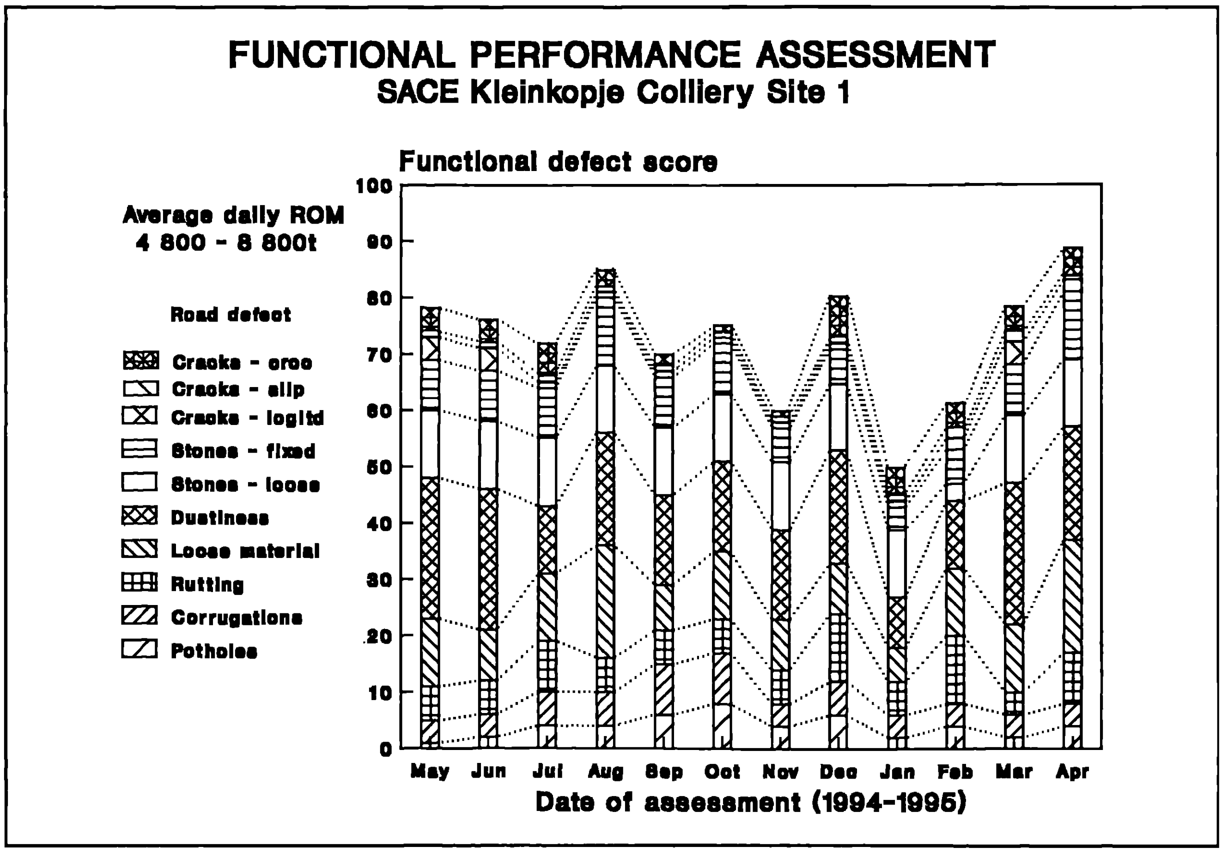


Figure 9.46 Functional Performance Assessment, Kleinkopje Colliery Site 1.

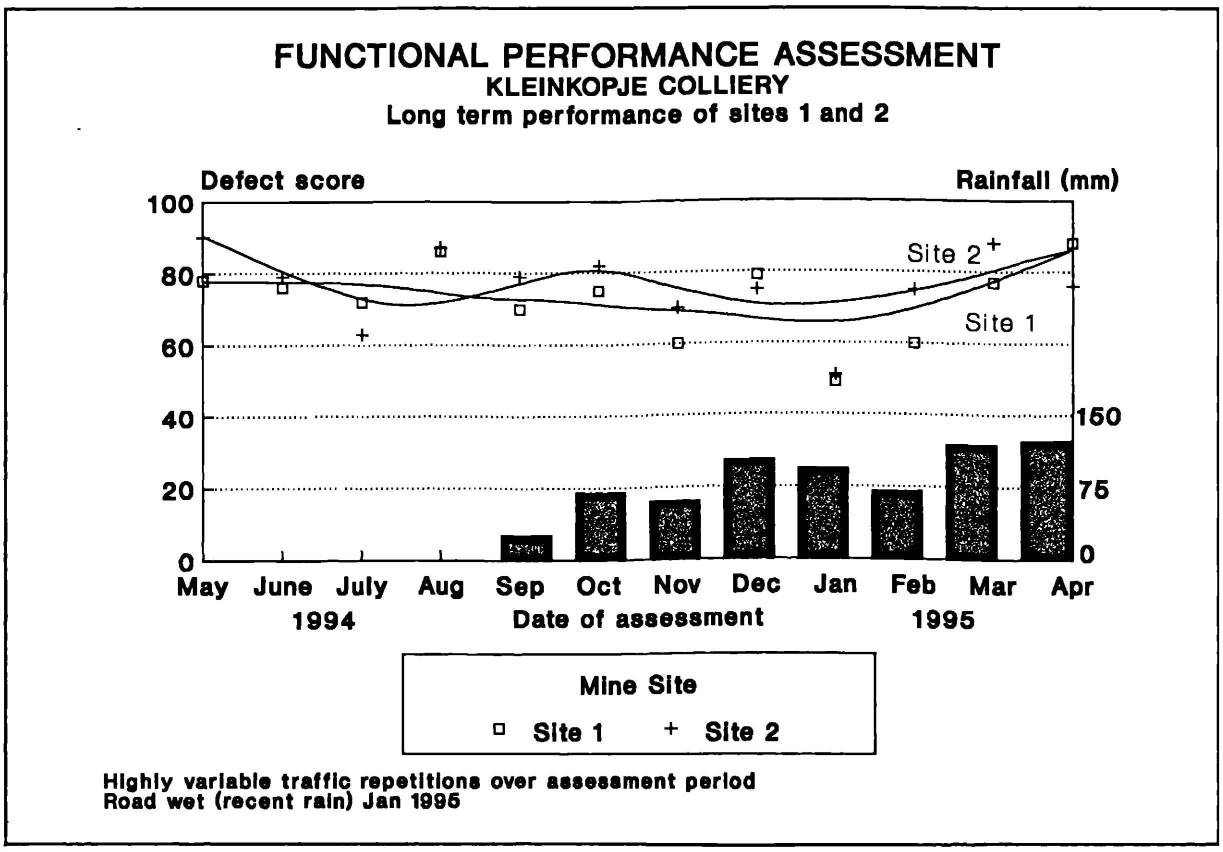


Figure 9.47 Long Term Performance Assessment, Kleinkopje Colliery Sites 1 and 2.

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.

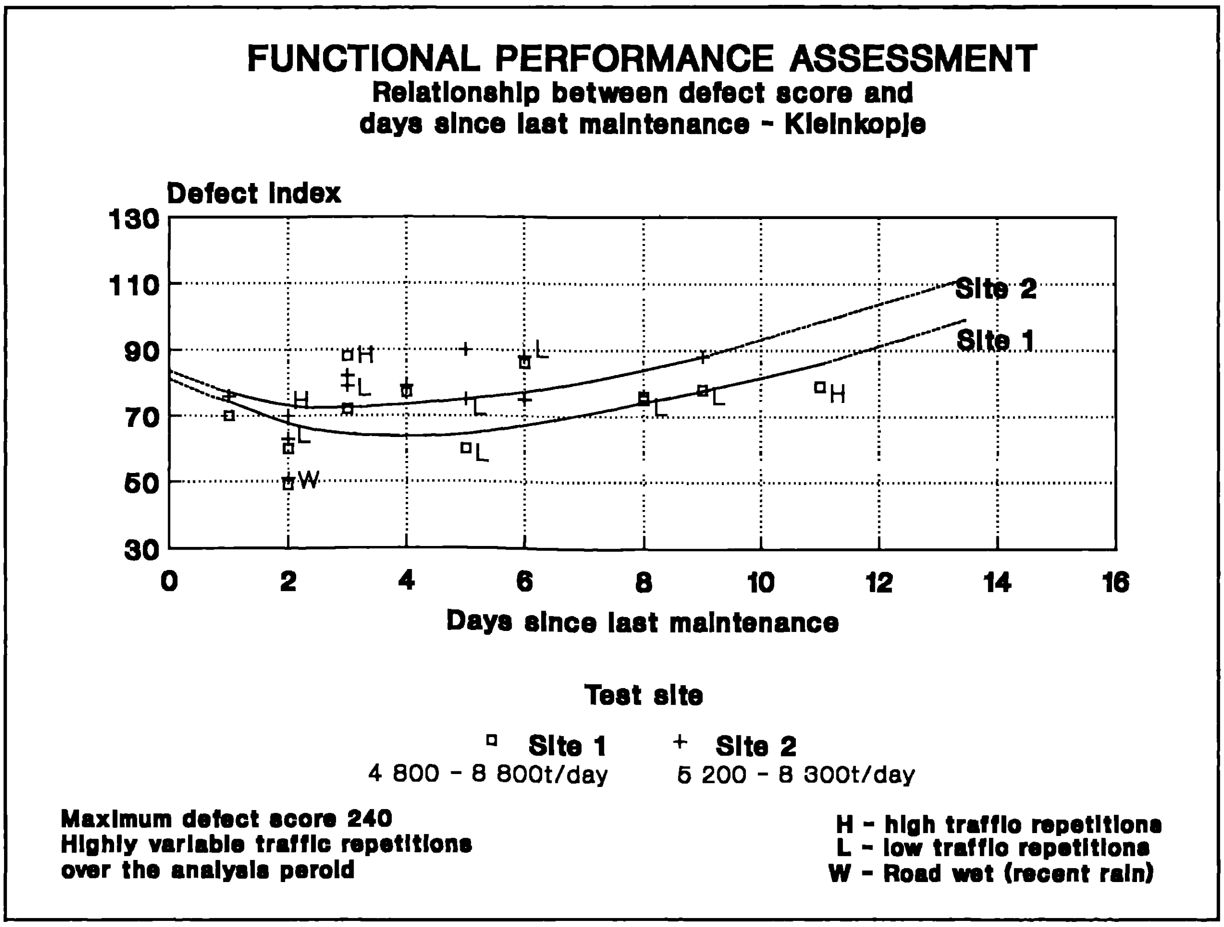


Figure 9.48 Effect of Maintenance on Defect Scores, Kleinkopje Colliery Sites 1 and 2.

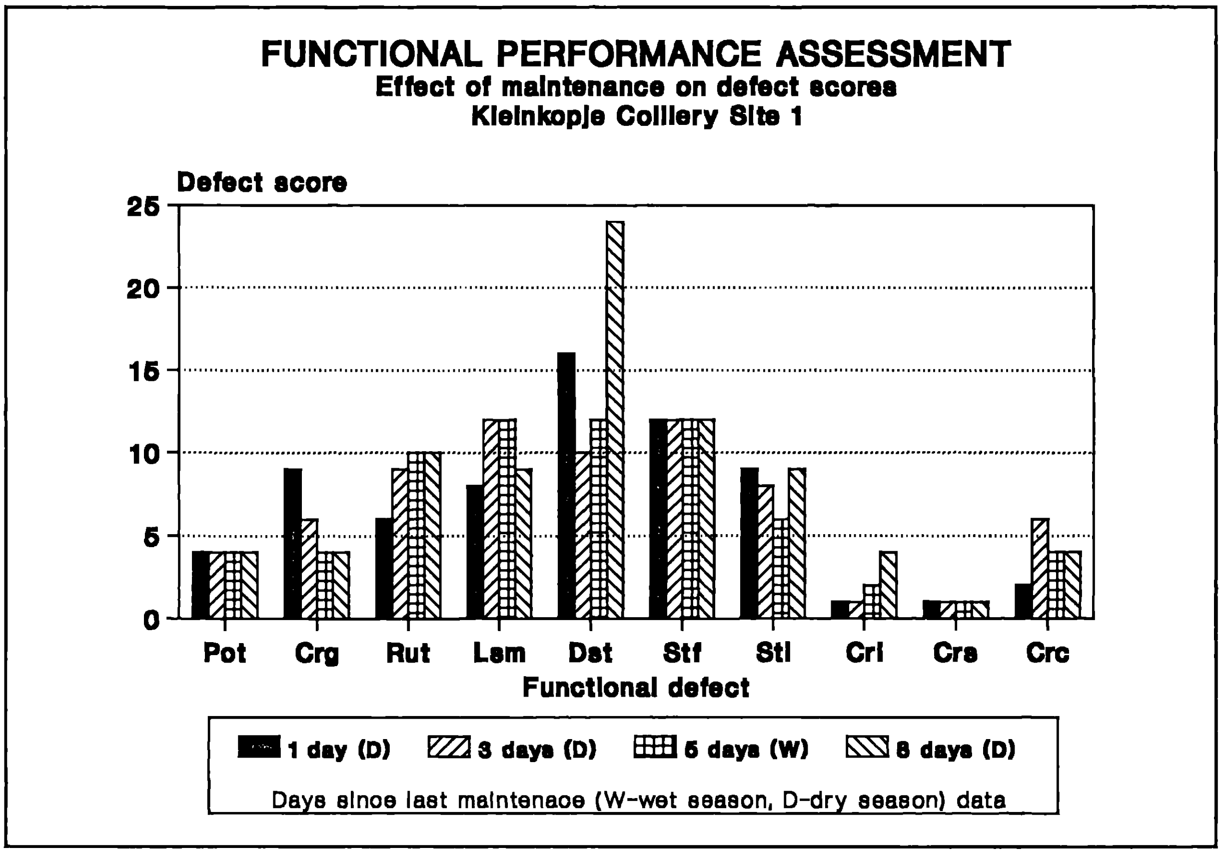


Figure 9.49 Effect of time since last maintenance on defect scores, Kleinkopje Colliery site 1.

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.

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 F4.

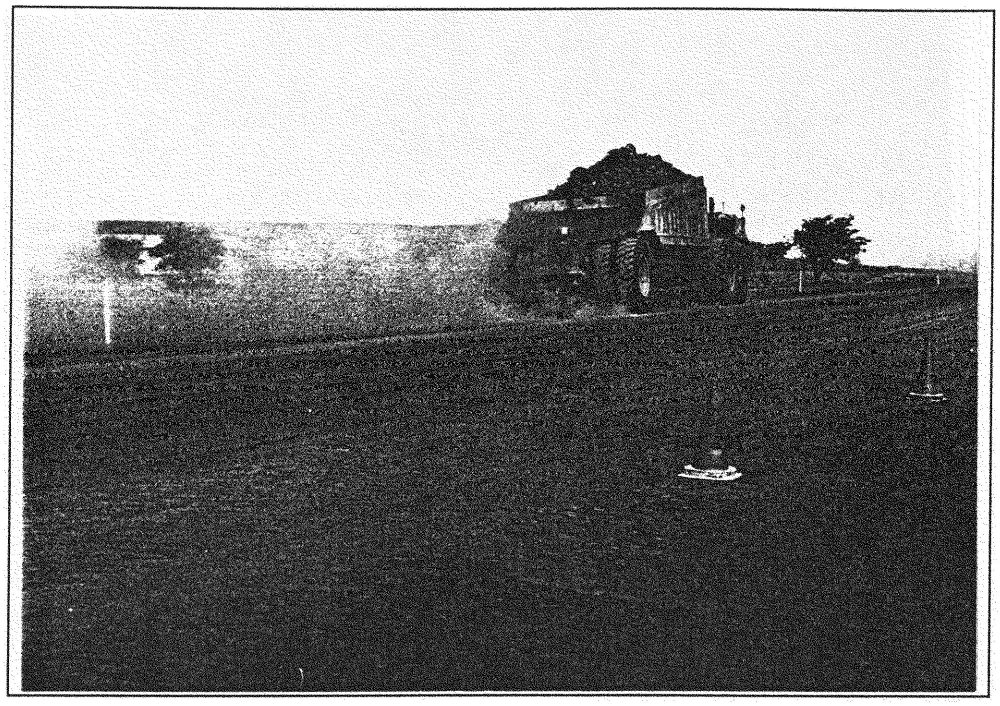


Figure 9.50 Typical dust defect problem, Kleinkopje Colliery site 1.

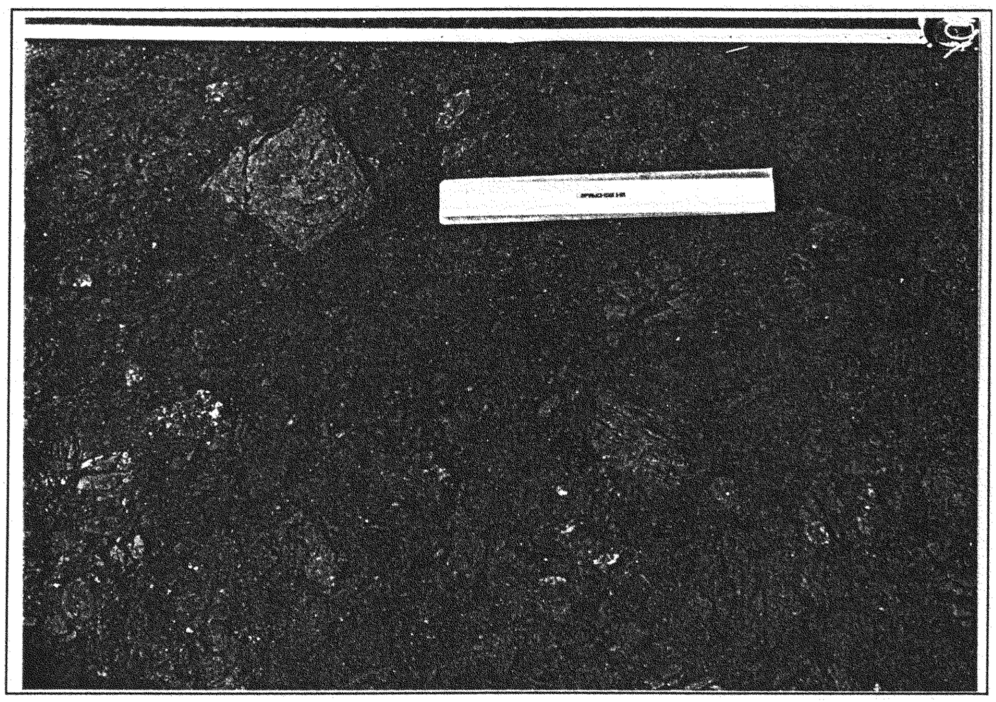


Figure 9.51 Fixed stoniness (after loose material removed), Kleinkopje Colliery Site 1.

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

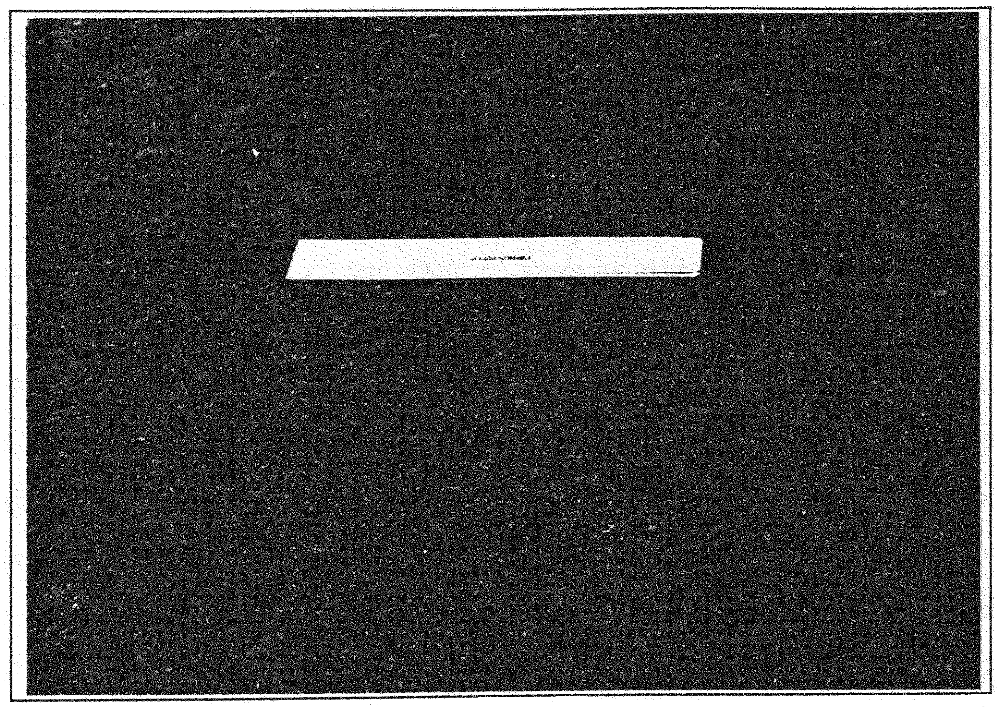
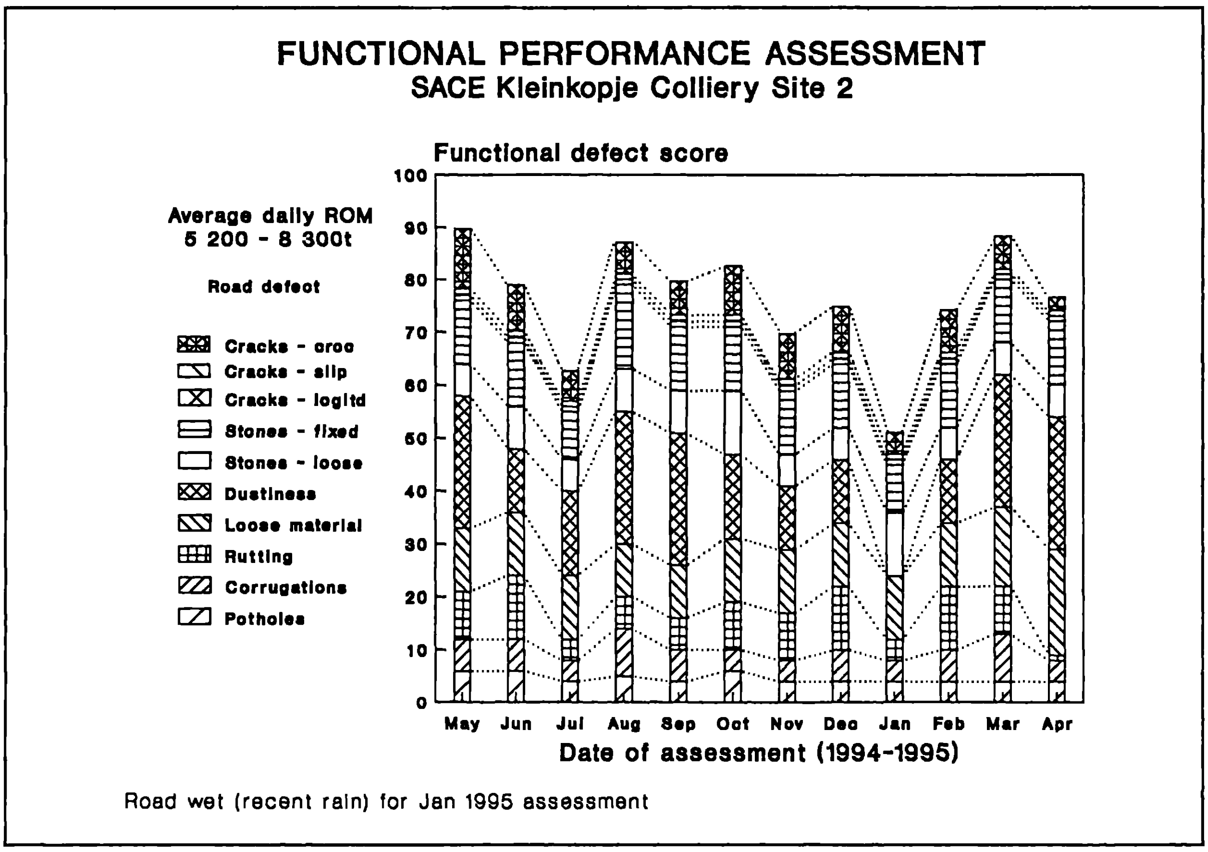


Figure 9.52 Uneven riding surface due to plucking of large stones and poor compaction of wearing course, Kleinkopje Colliery Site 1.



Road wet (recent rain) for Jan 1995 assessment

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

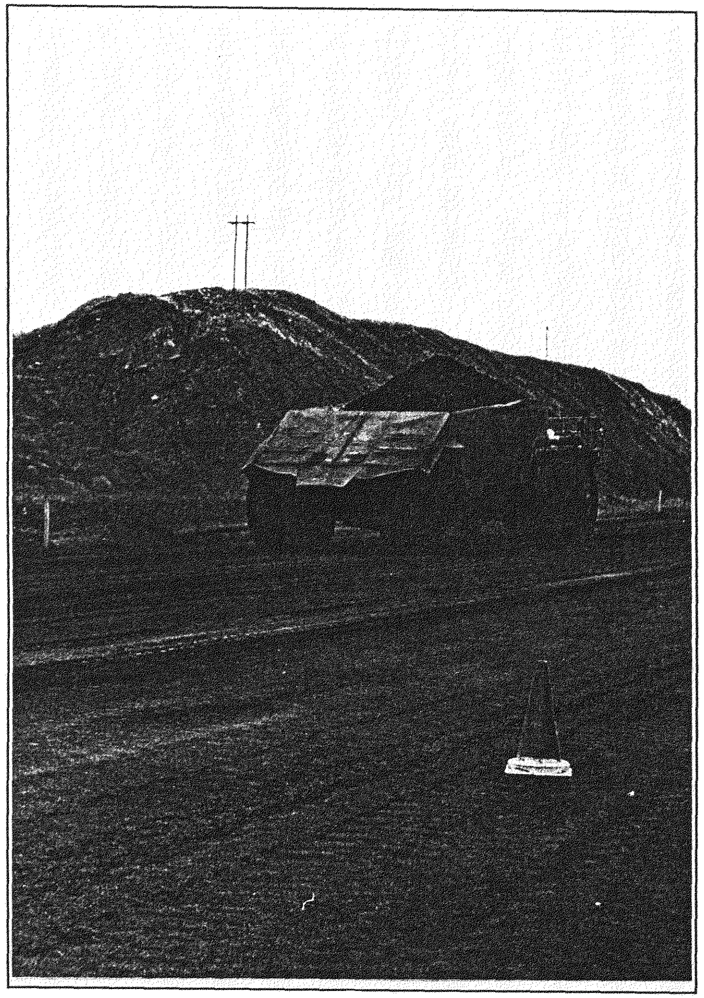


Figure 9.54 Difference in character between laden and unladen carriageways when wet, Kleinkopje Colliery Site 2.

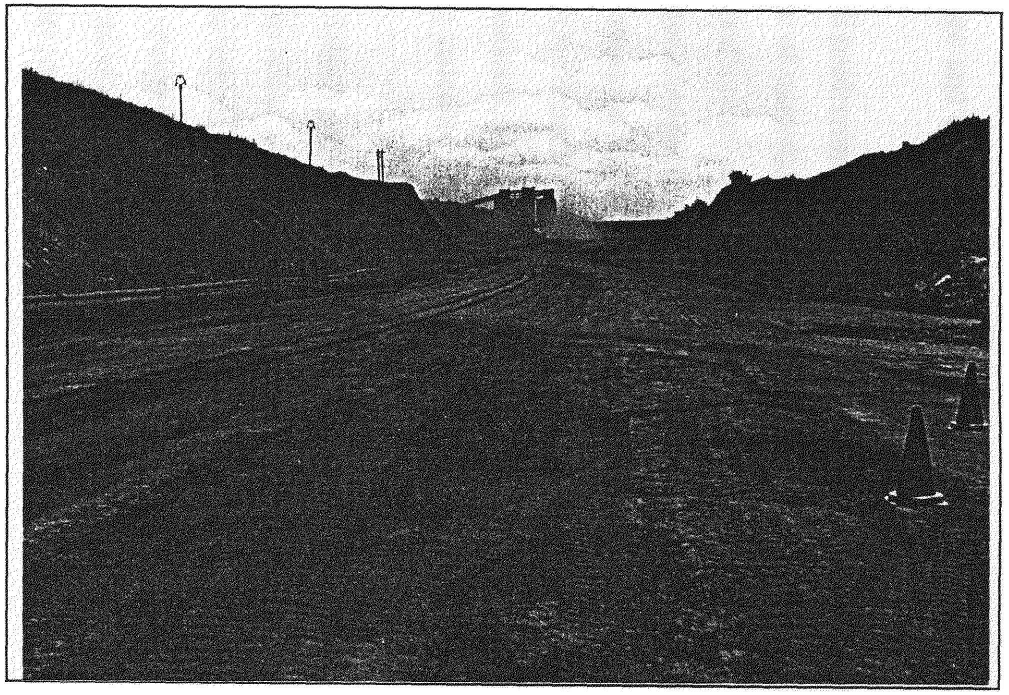


Figure 9.55 Condition of wearing course after blading, Kleinkopje Colliery Site 2.

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.

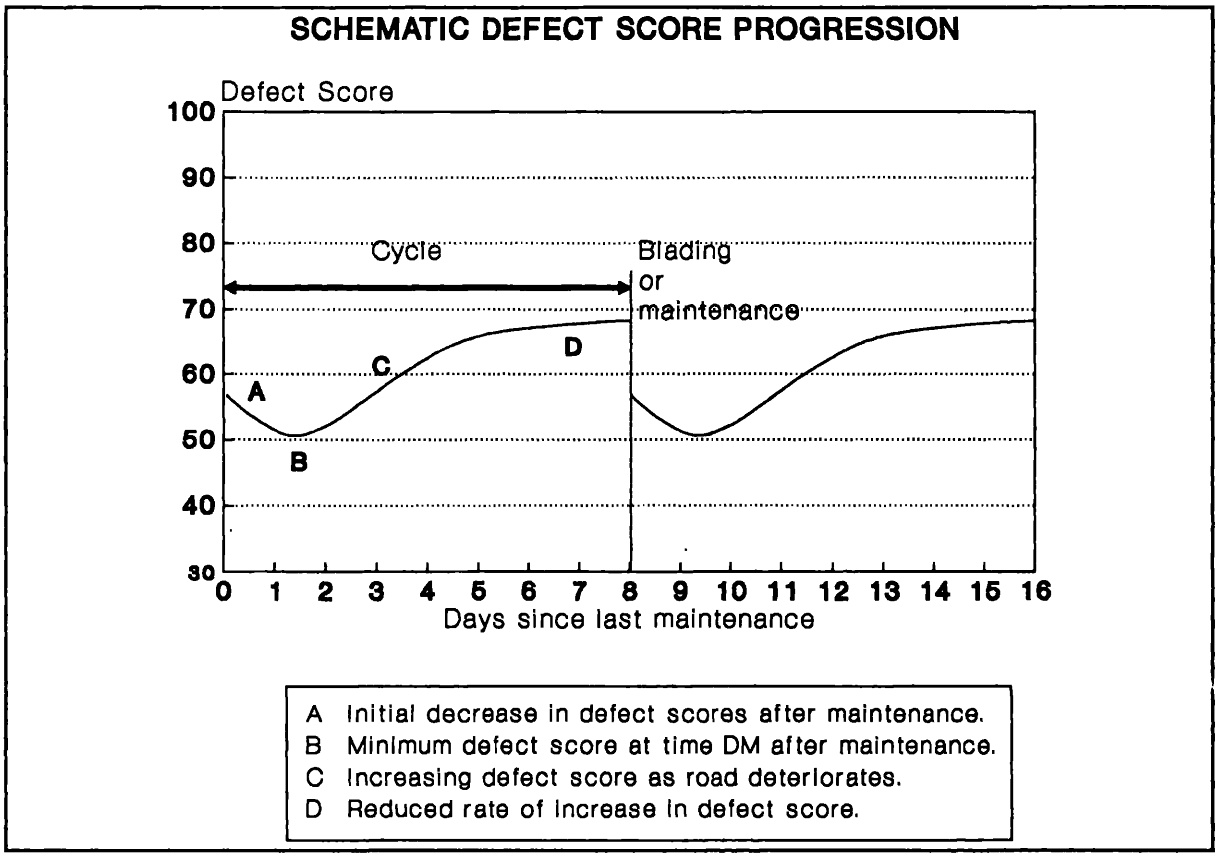


Figure 10.1 Schematic illustration of the development of defect score on a haul road.

(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.

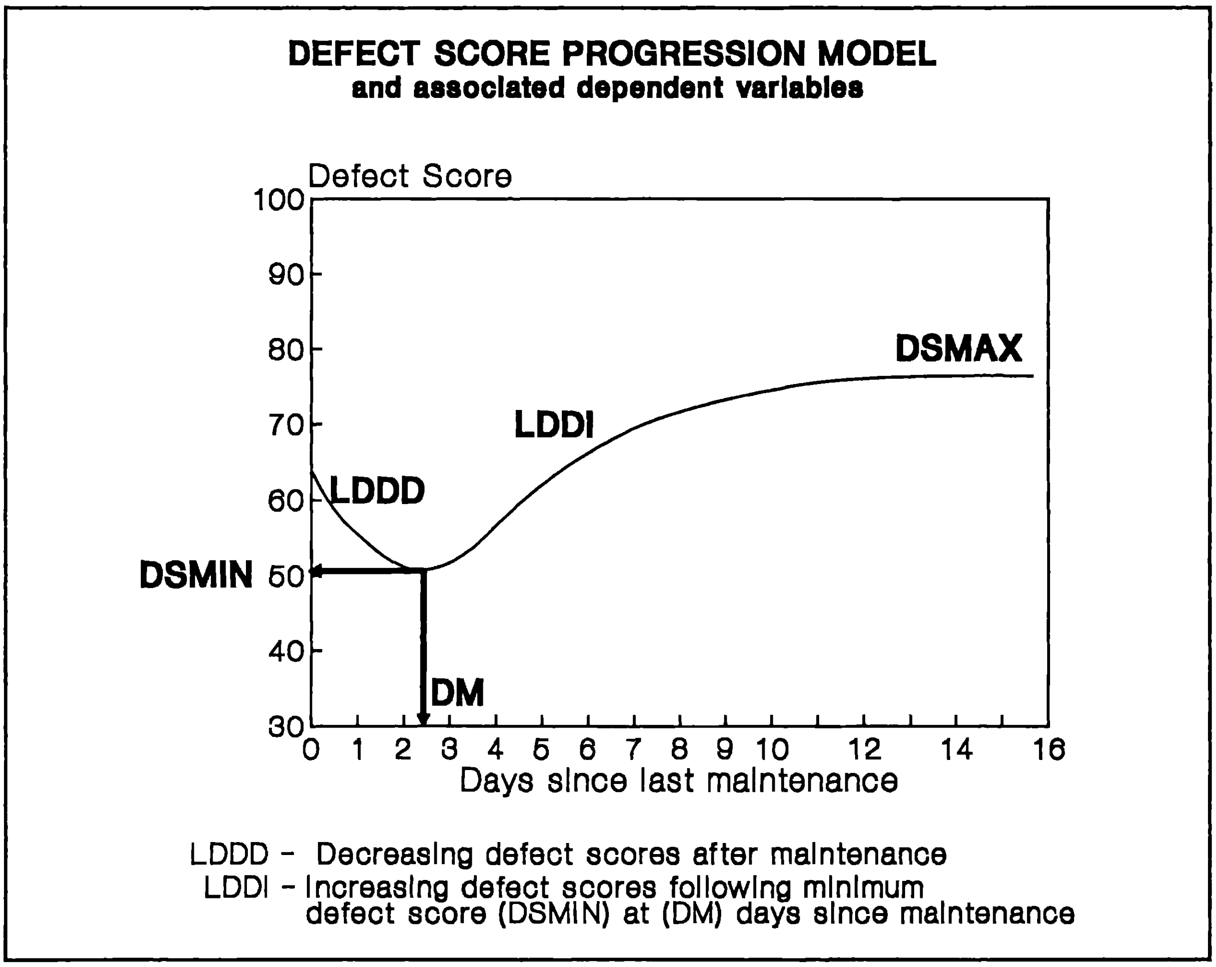


Figure 10.2 Selection of model and dependant variables for defect score progression

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:

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

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:

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

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.

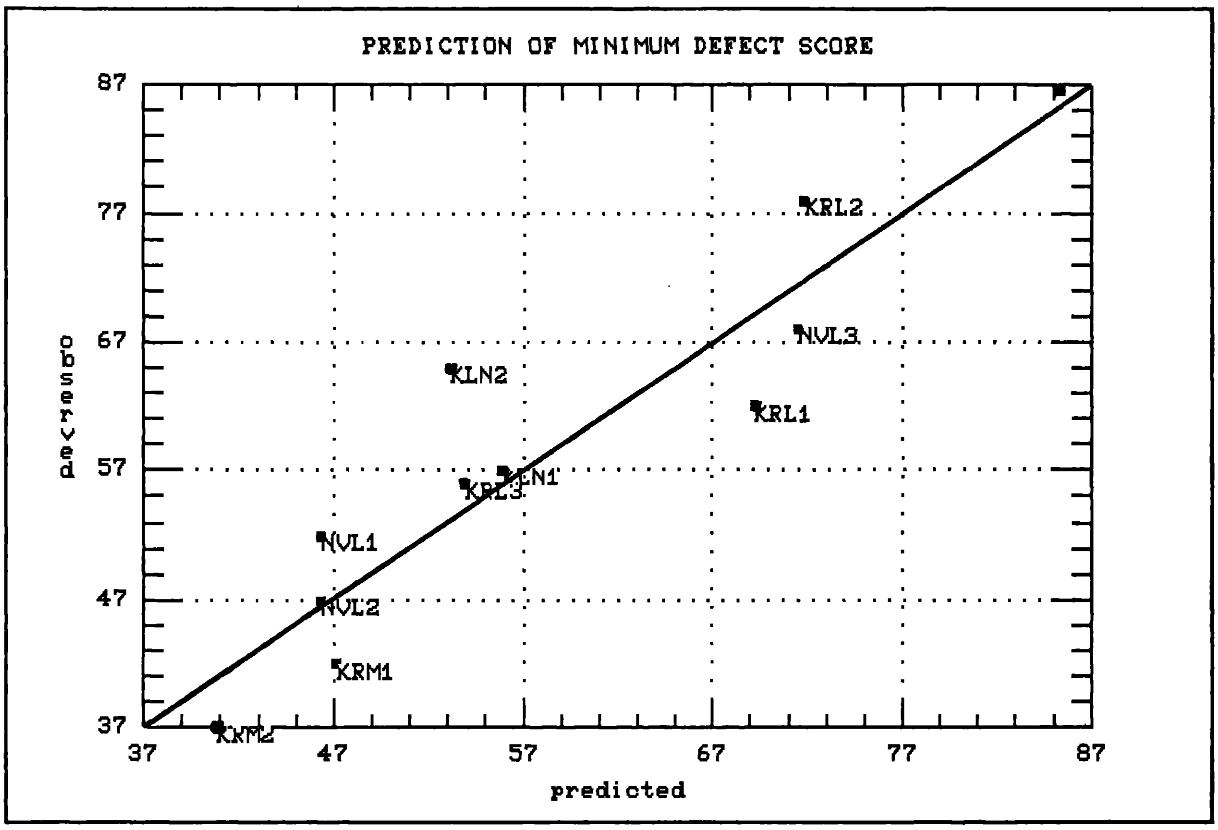


Figure 10.3 Goodness of fit for model (2) for DSMIN

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.

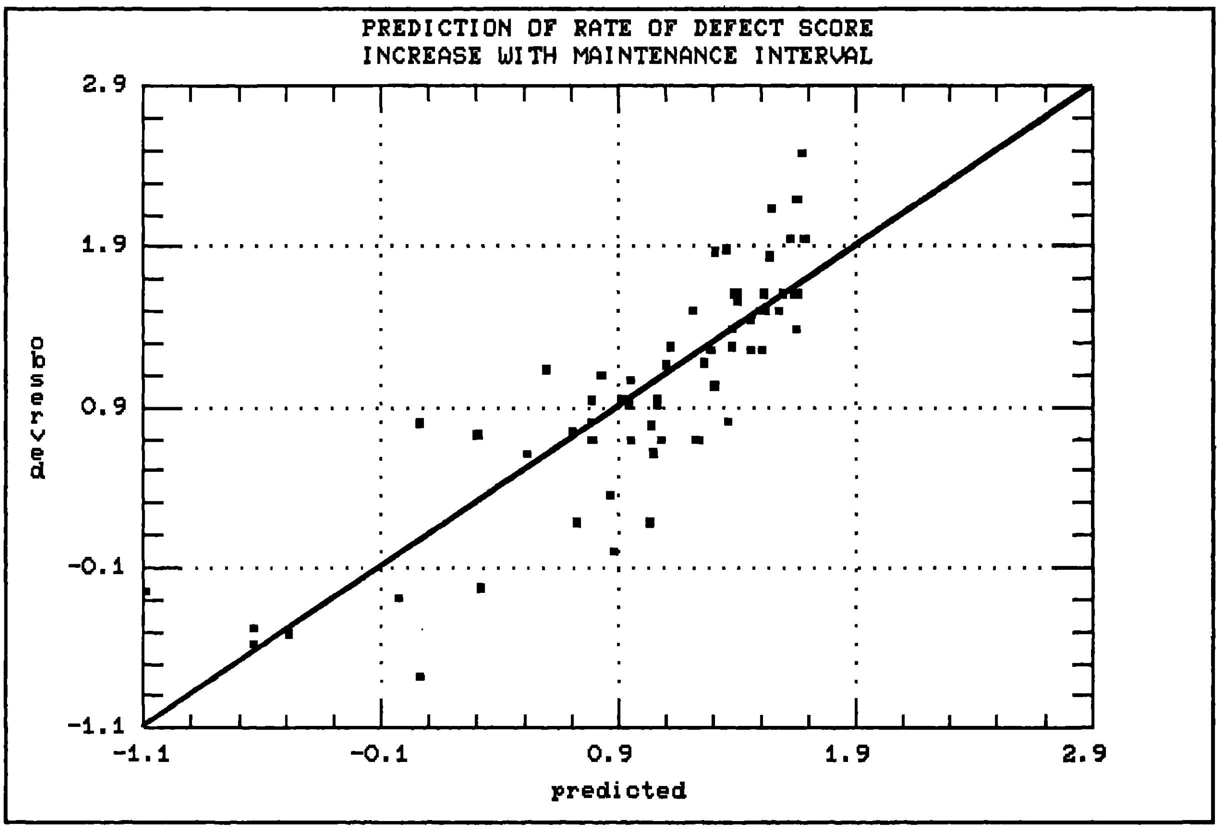


Figure 10.4 Goodness of fit for model (3) for LDDI

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 (95th 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.

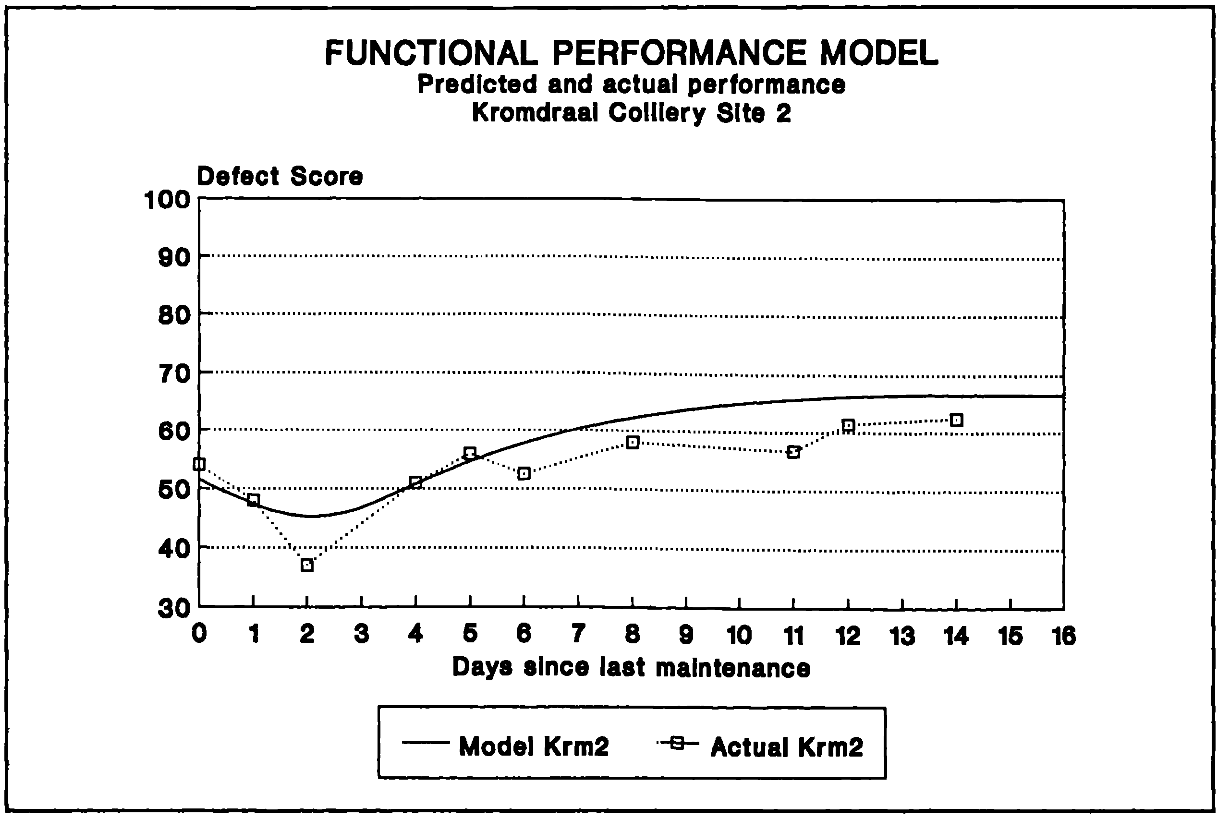


Figure 10.5 Estimation Characteristics of Prediction Model for Rate of Increase in Defect Score as Applied at Kromdraai Mine Site 2.

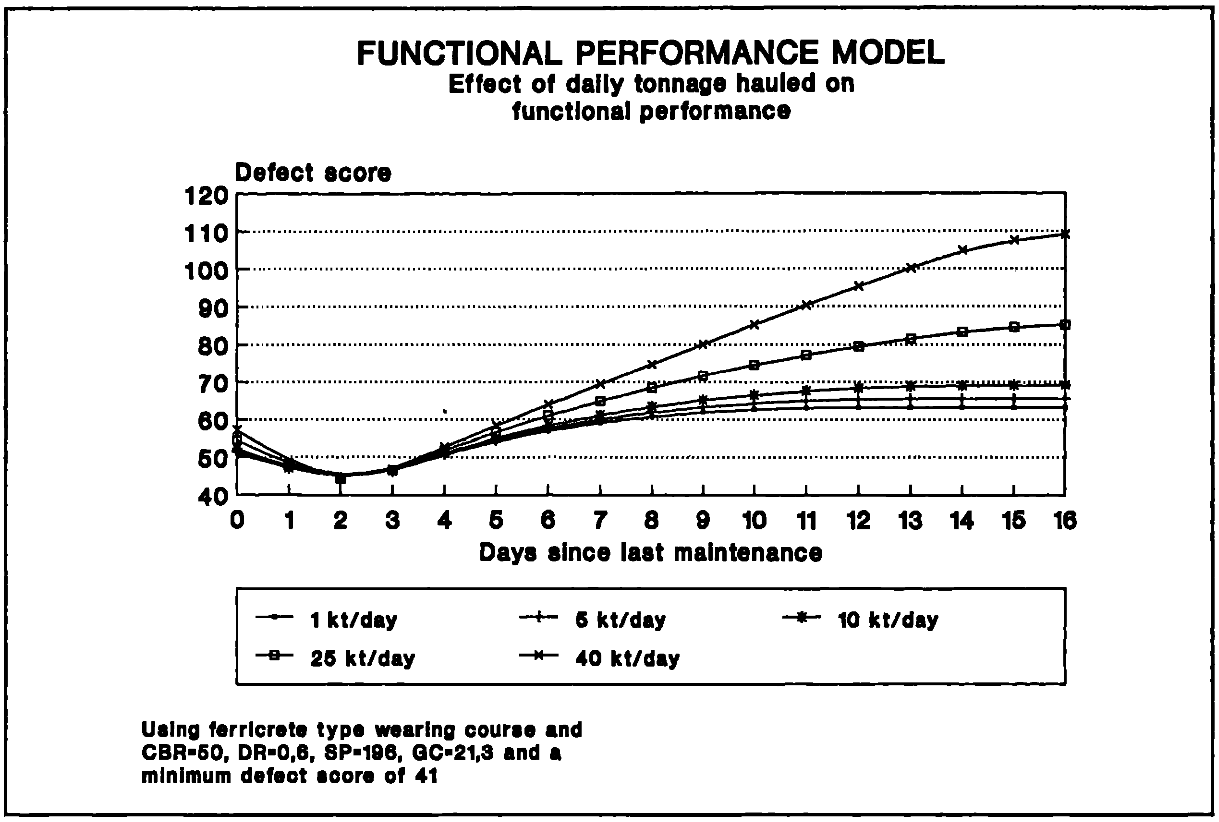


Figure 10.6 Effect of Increasing Traffic Volume on Defect Score Progression.

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.

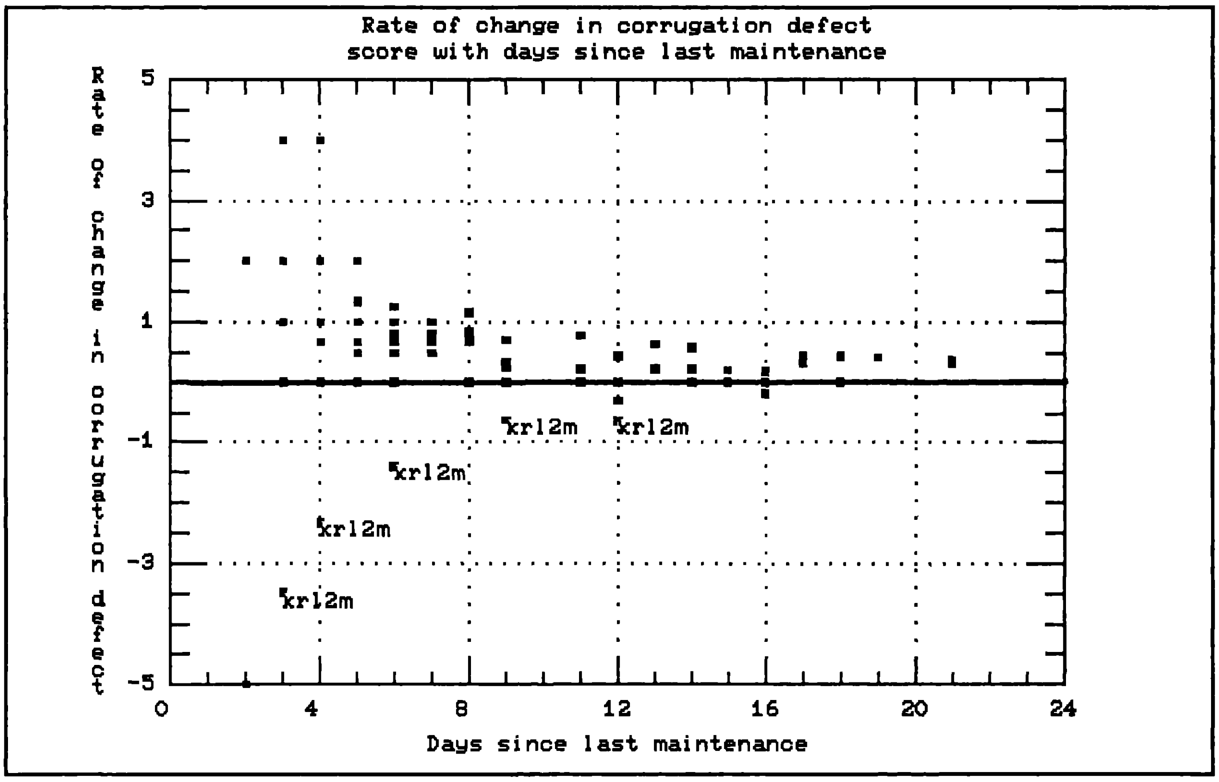


Figure 10.7 Rate of change of corrugation defect score with days since last maintenance.

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

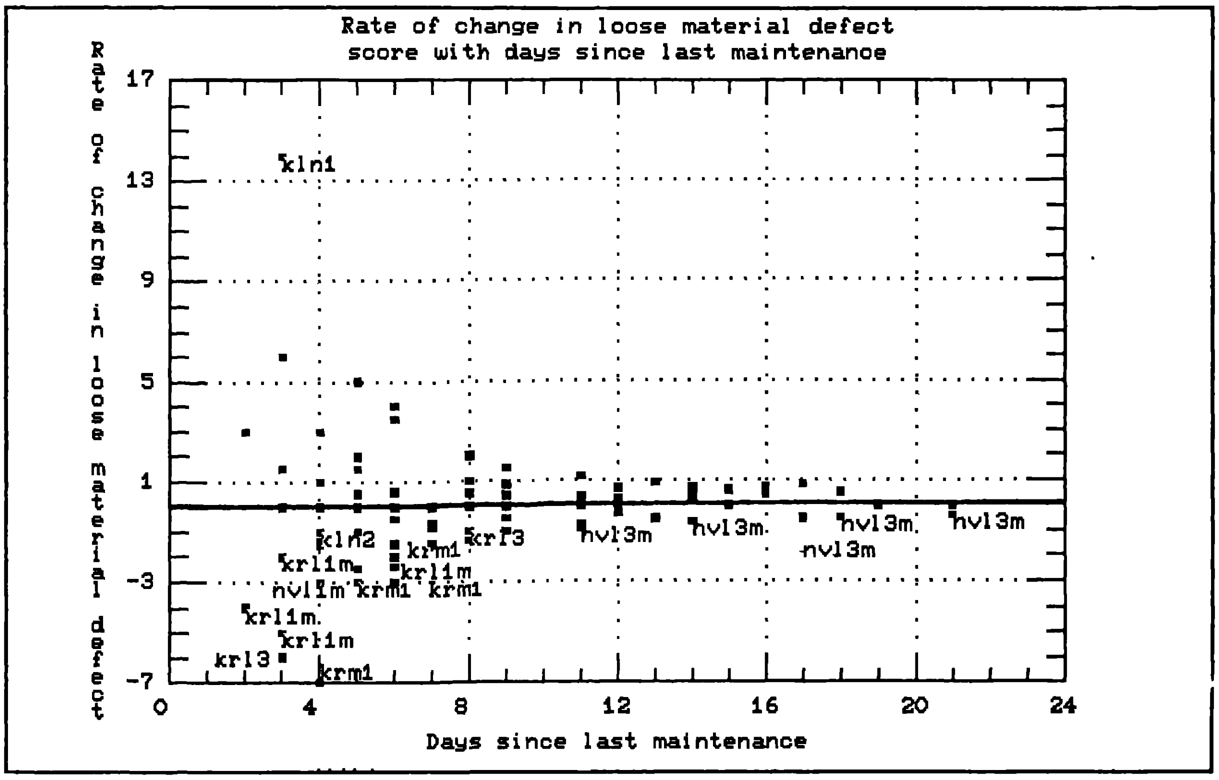


Figure 10.8 Rate of change of loose material defect score with days since last maintenance.

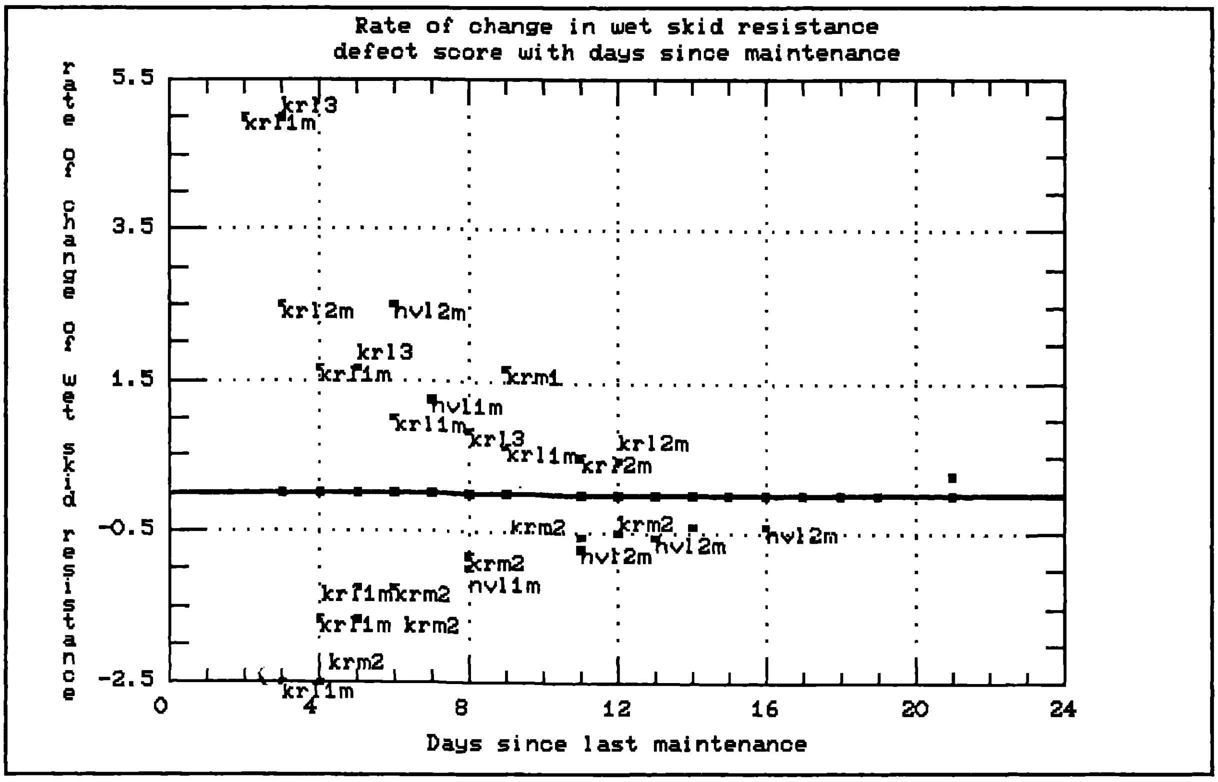


Figure 10.9 Rate of change of wet skid resistance defect score with days since last maintenance.

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.

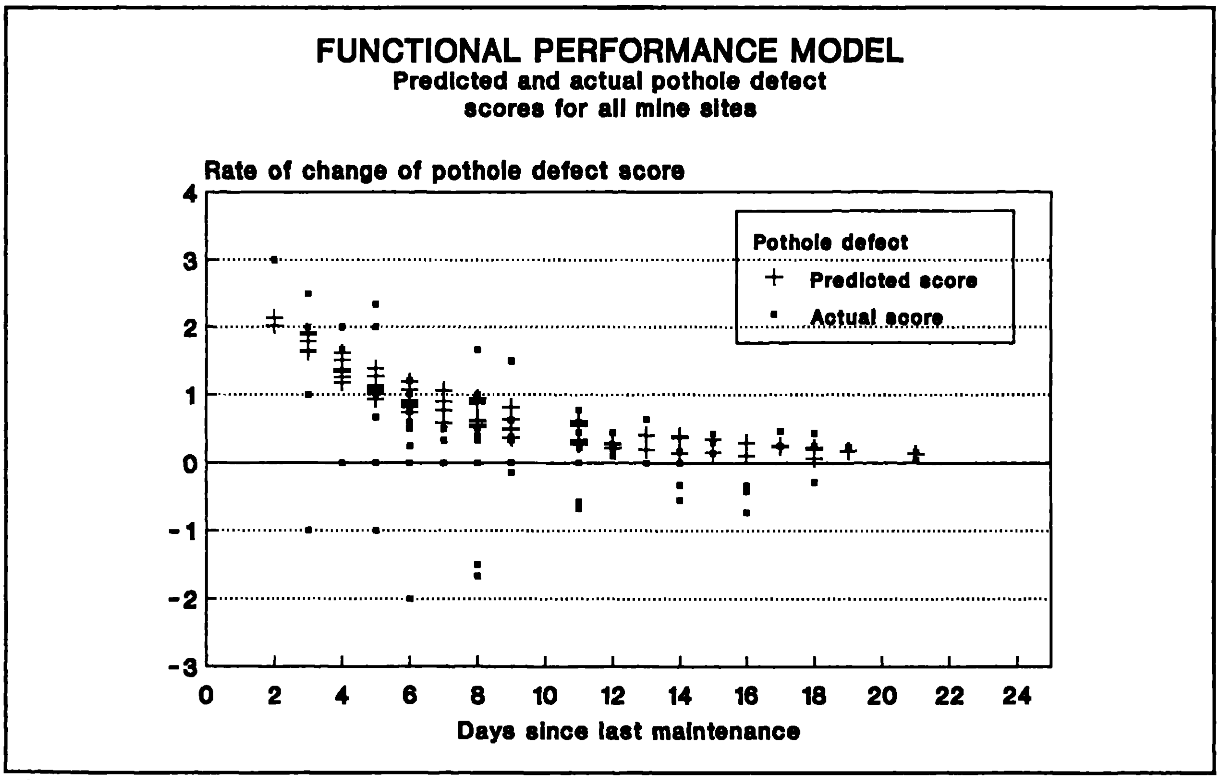


Figure 10.10 Comparison of predicted and actual pothole defect scores for all mine sites

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;

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

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

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

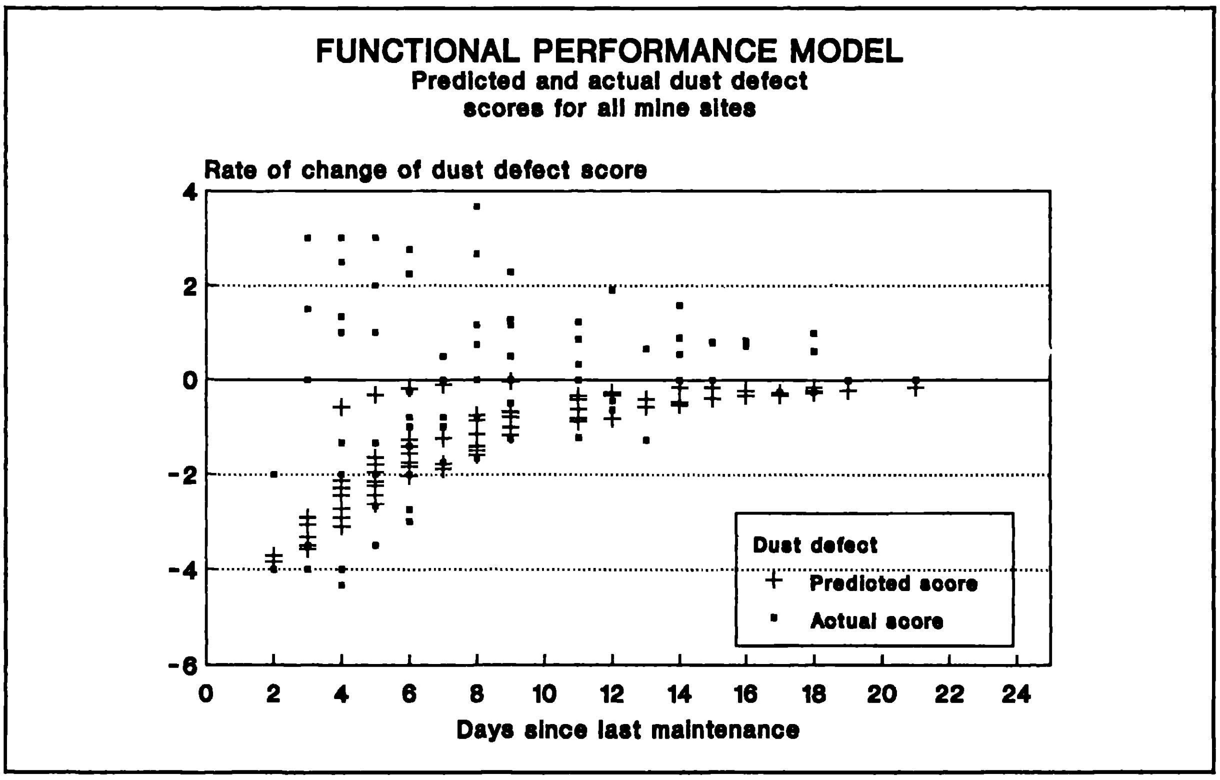


Figure 10.11 Comparison of predicted and actual dust defect scores for all mine sites (assuming decreasing defect scores with time)

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.

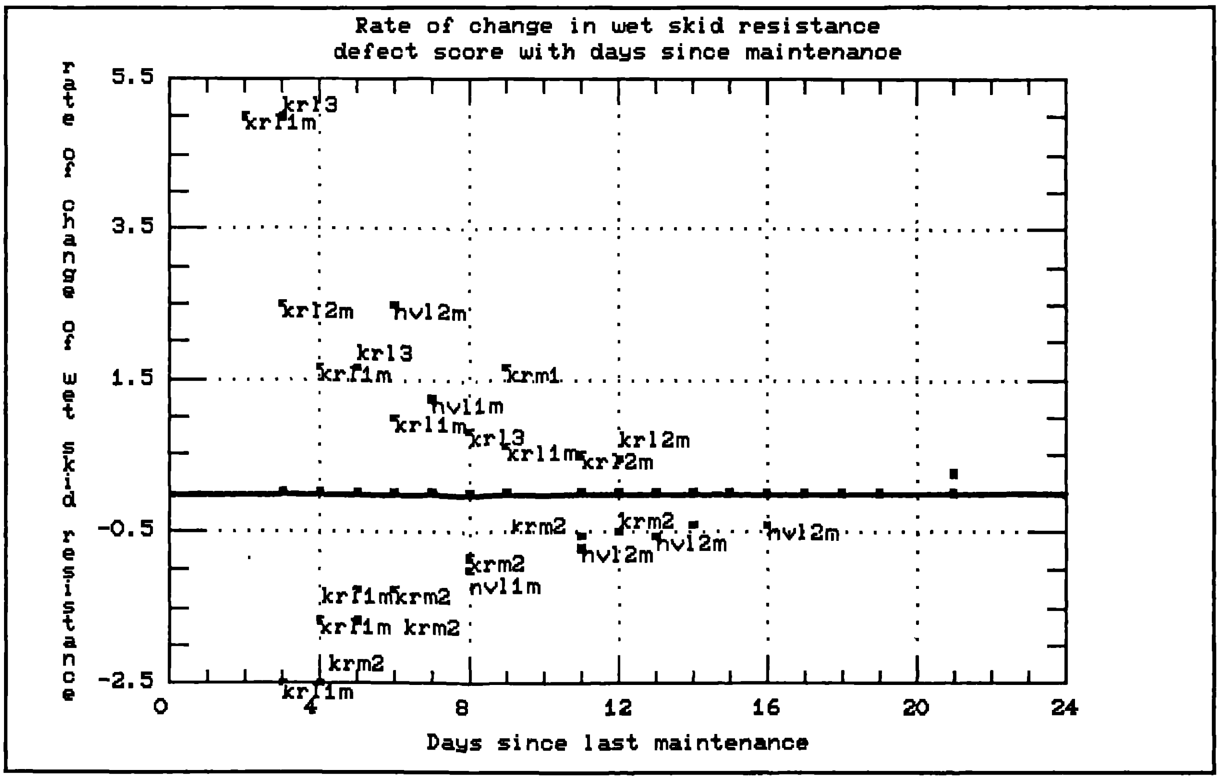


Figure 10.12 Rate of change of wet skid resistance defect score with days since last maintenance.

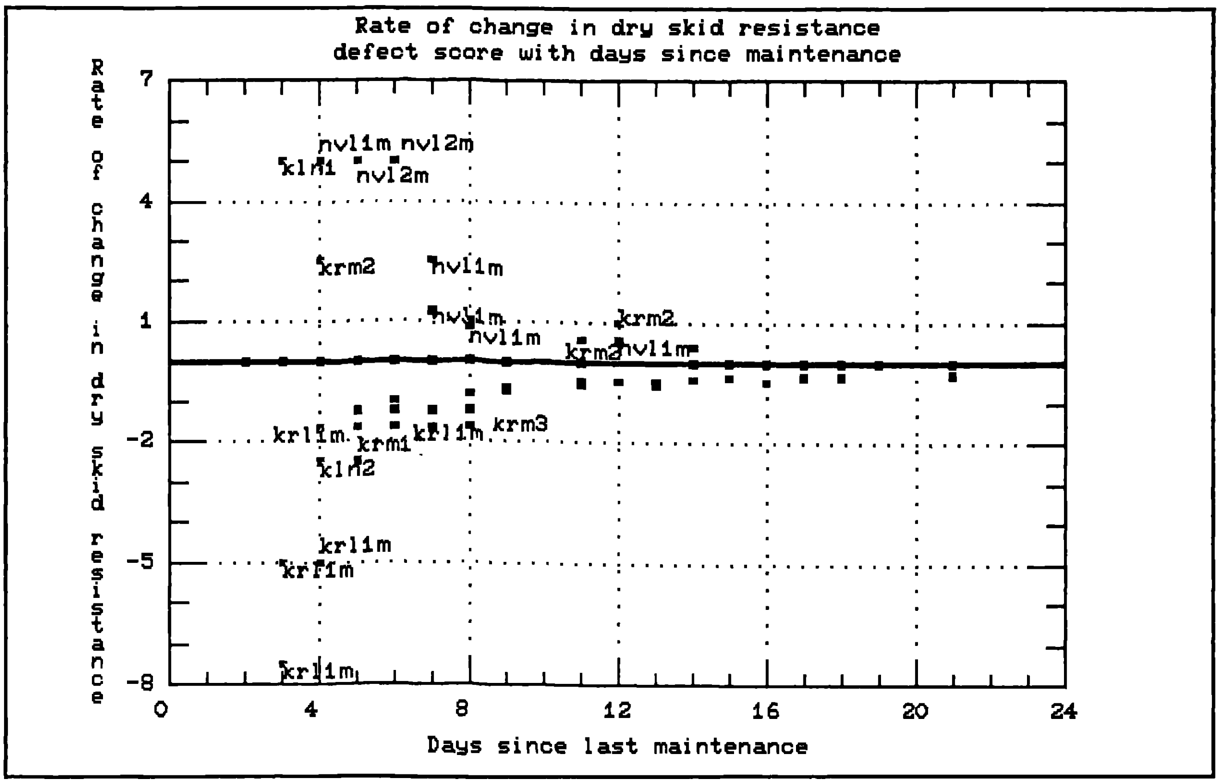


Figure 10.13 Rate of change of dry skid resistance defect score with days since last maintenance.

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

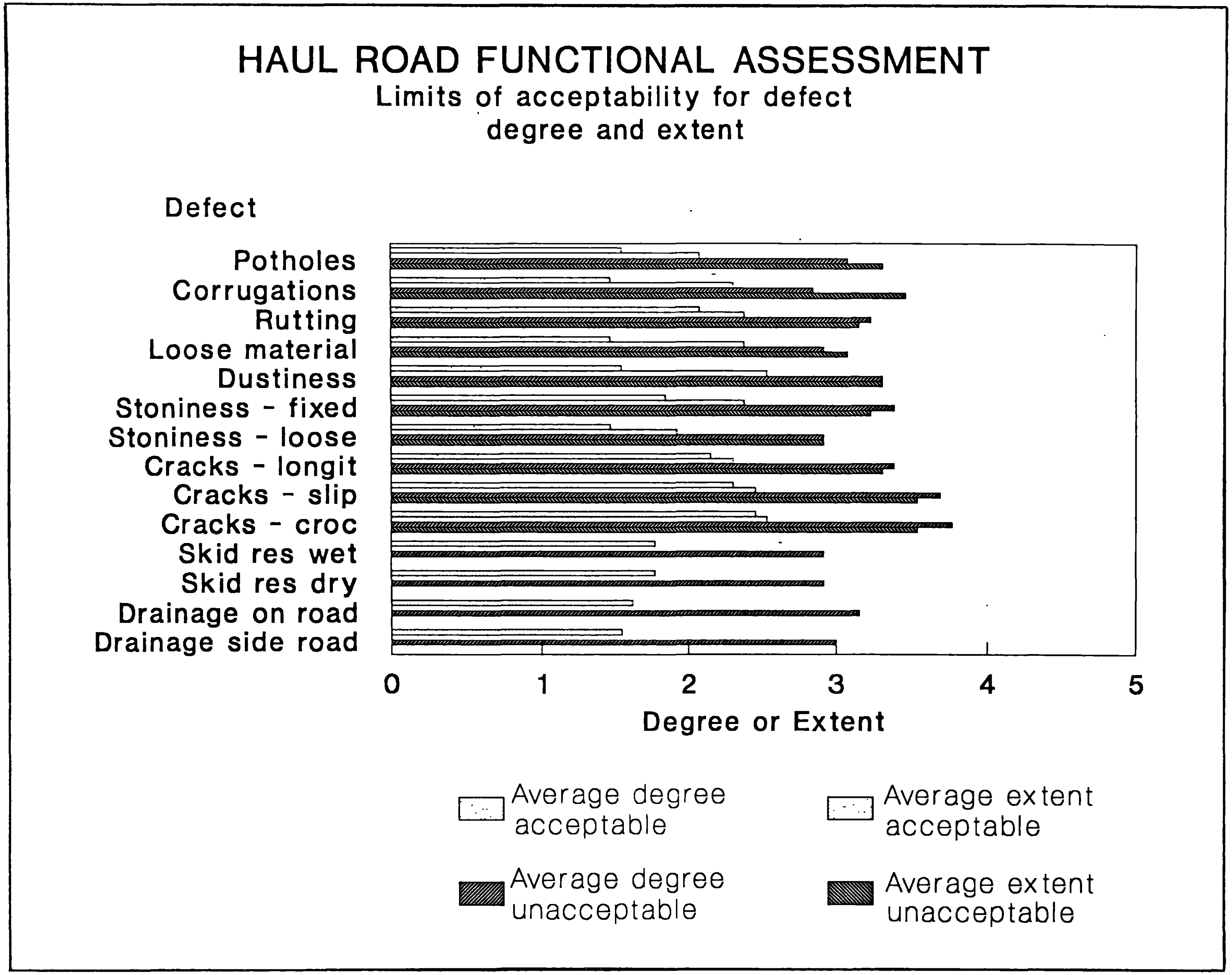


Figure 11.1 Limits of Acceptability for Defect Degree and Extent

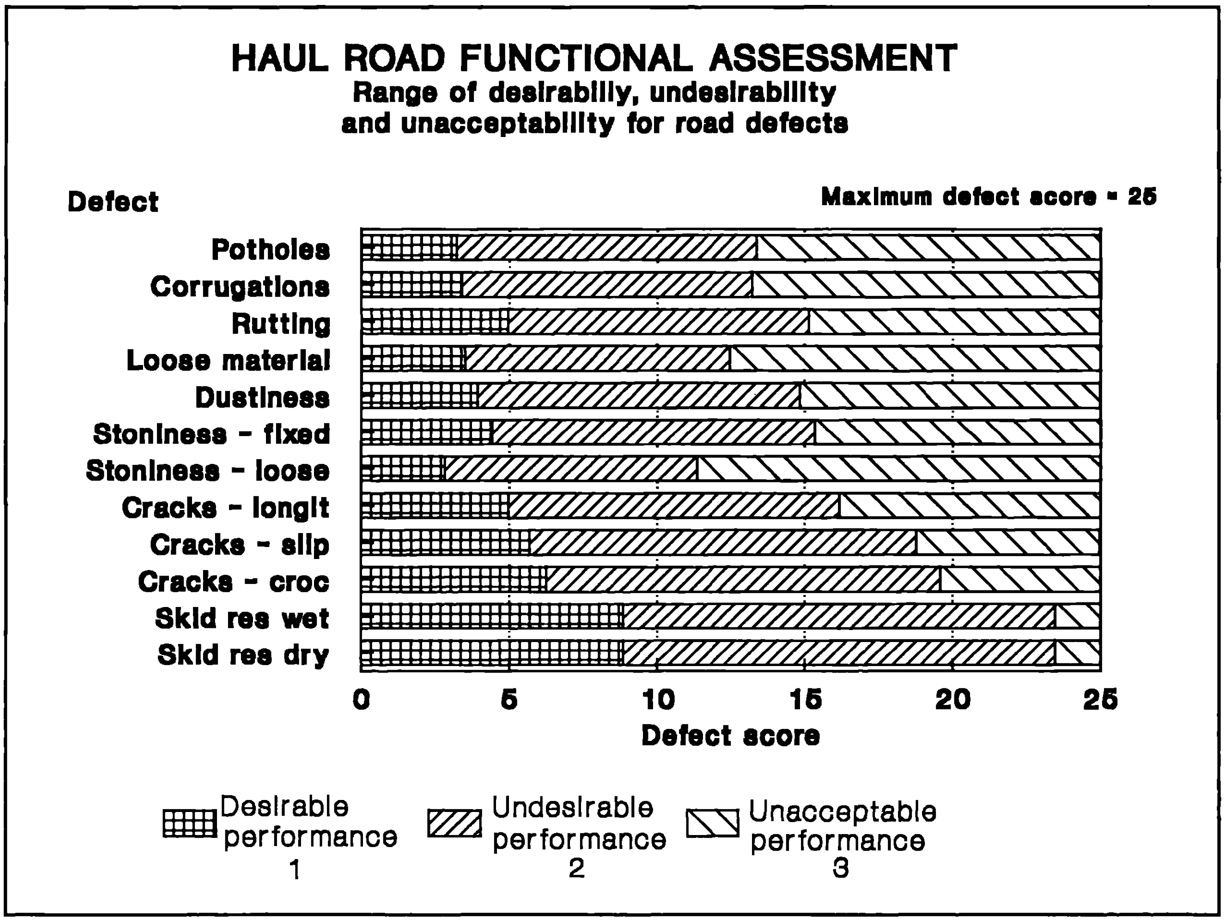


Figure 11.2 Limits of Defect Functional Performance

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

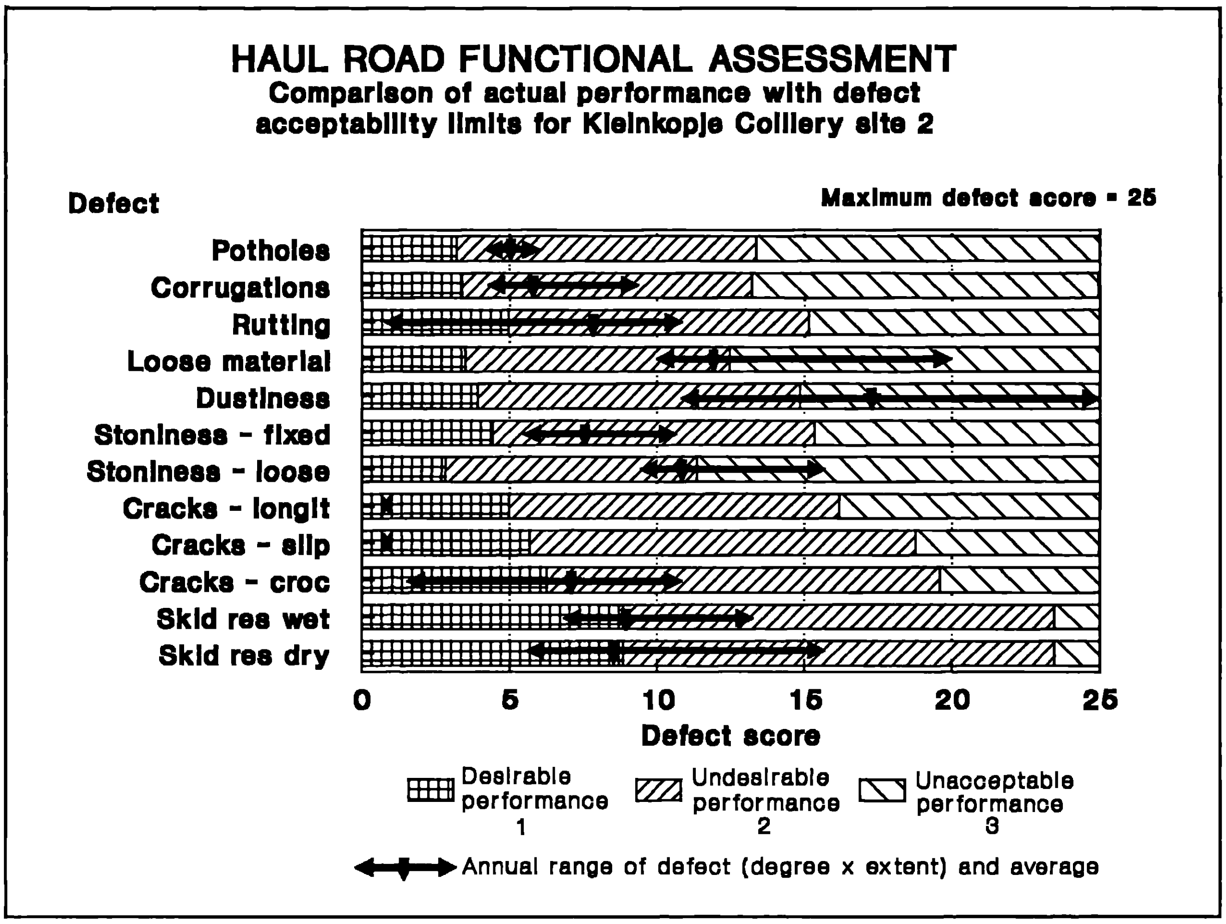


Figure 11.3 Range and Annual Average Values for Mine Test Site Functional Performance in Relation to Established Performance Limits.

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

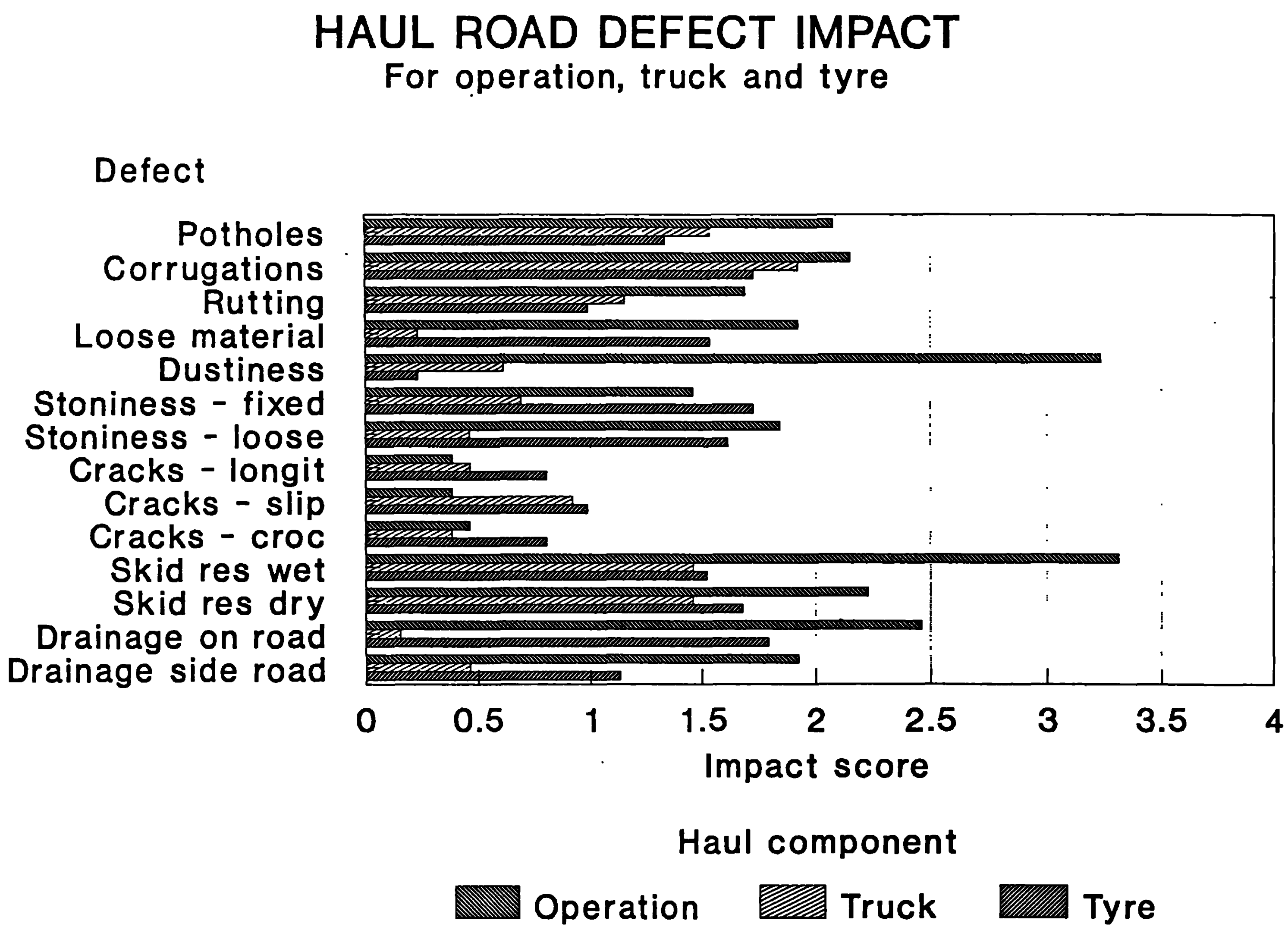
1	Desirable performance
2	Undesirable performance
3	Unacceptable performance

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



Refer to tabulation of impacts for implication of impact score for each haul component.

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 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.

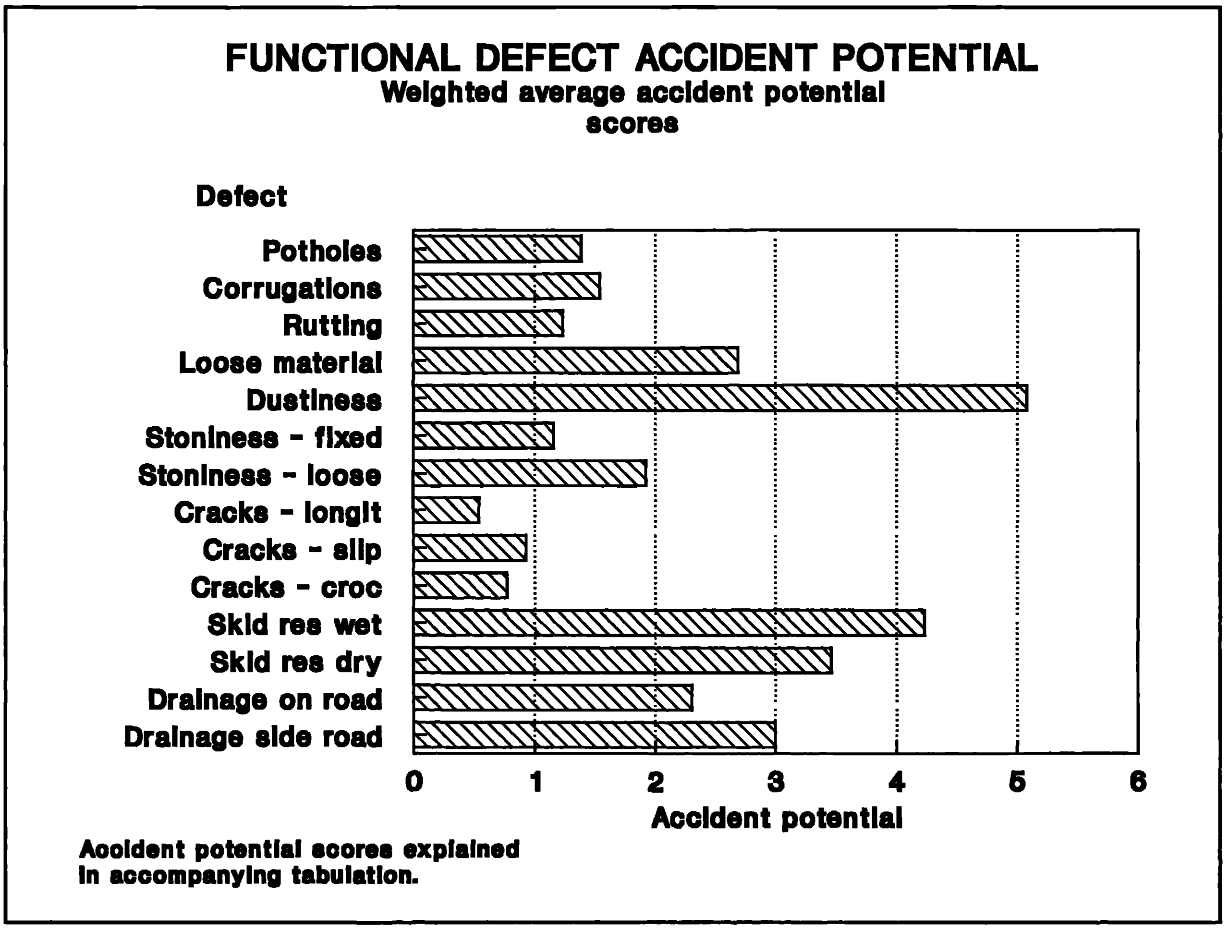


Figure 11.5 Accident Potential of Haul Road Functional Defects.

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

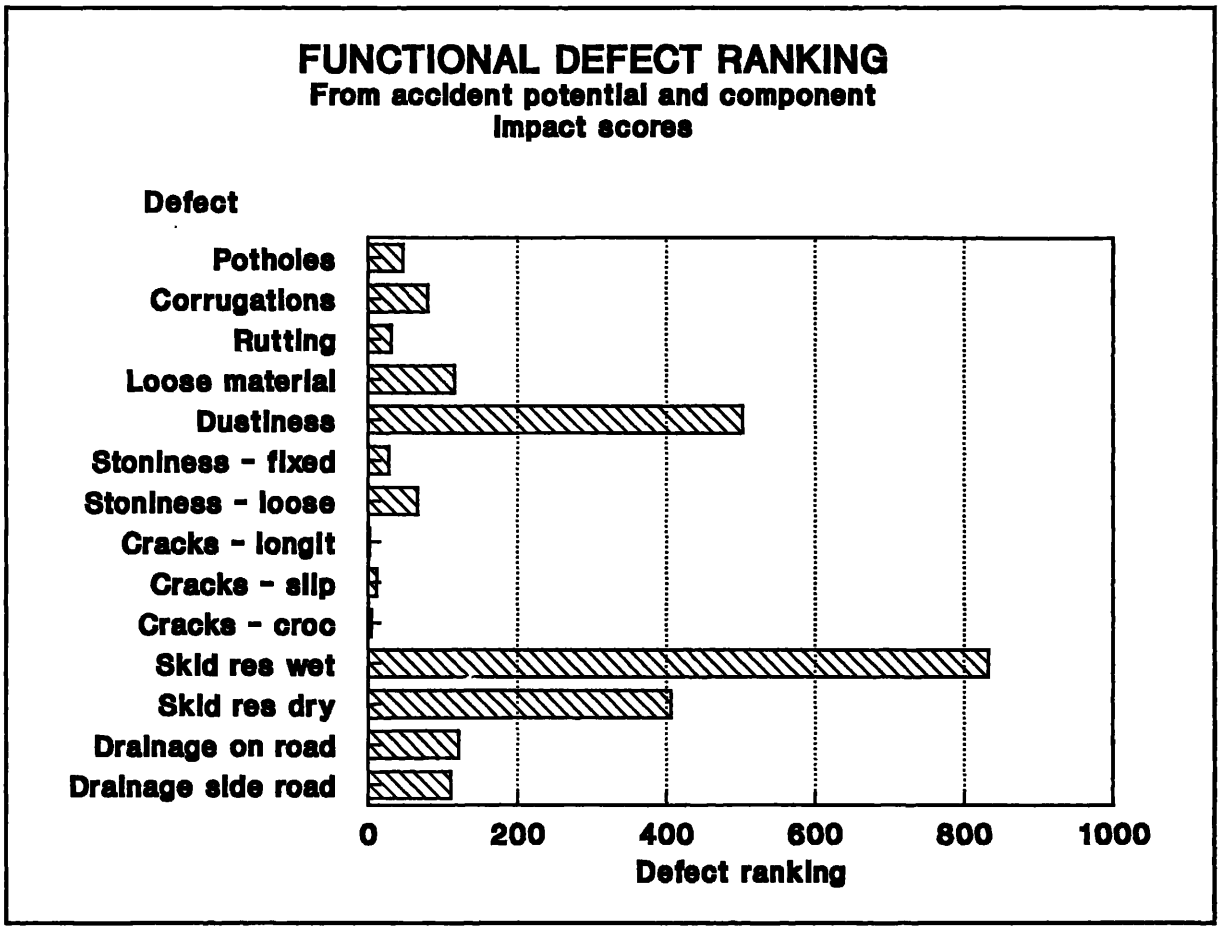


Figure 11.6 Ranking of Haul Road Defects

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.