# CHAPTER 12

# DERIVATION OF WEARING COURSE MATERIAL SPECIFICATIONS

## 12.1 Introduction

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

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

## 12.2 Specification Requirements

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

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

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

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

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

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

### 12.2.1 Performance Ranking

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

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

**Table 12.1** Categorisation of Functional Performance Limits

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

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

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

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

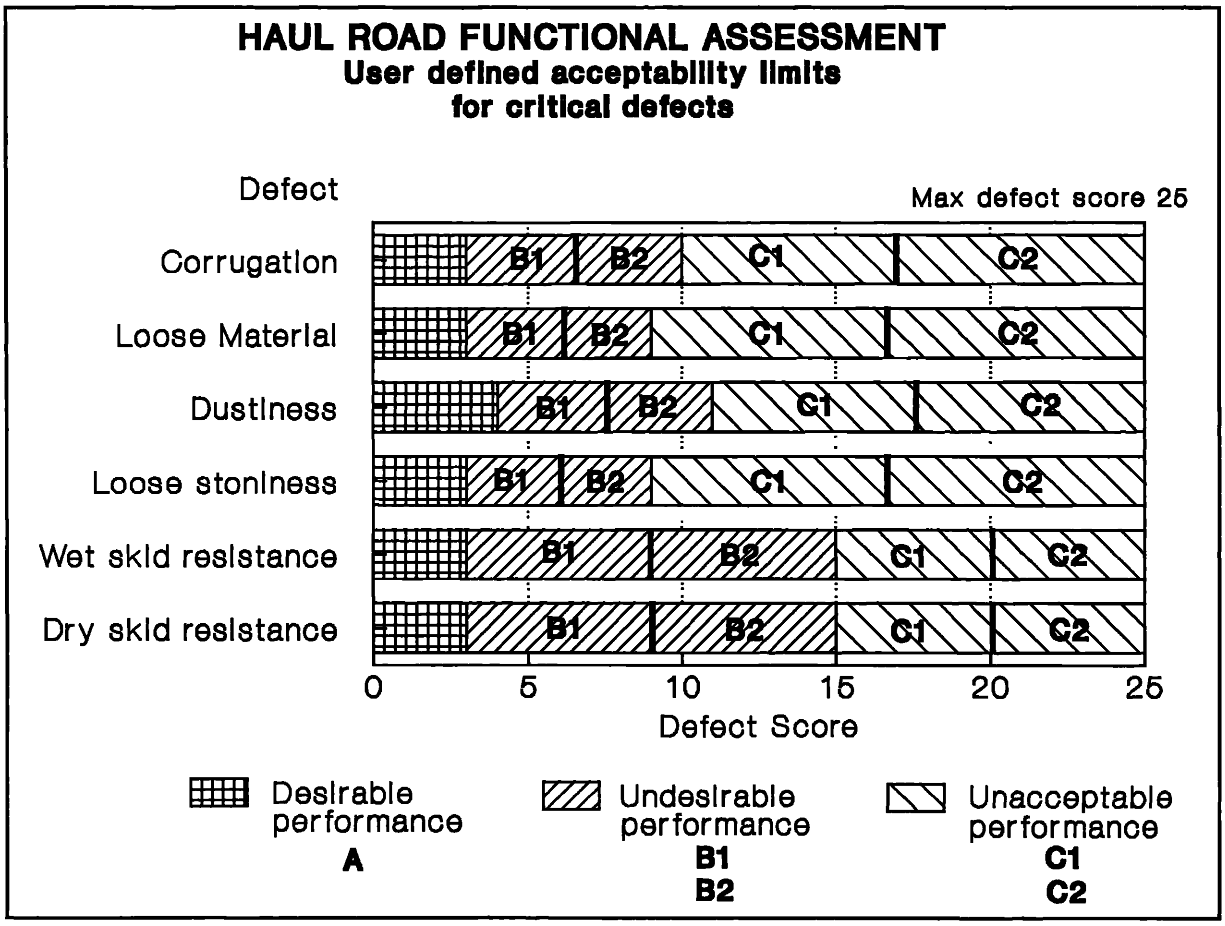


**Figure 12.1** Graphical Representation of Defect and Overall Road Functional Performance Classification.

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

**Table 12.3** Acceptability Limits for Critical Functional Defects.

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

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

**Table 12.4** Acceptability Limits for Overall Functional Performance.

| ACCEPTABILITY LIMITS FOR OVERALL HAUL ROAD FUNCTIONAL PERFORMANCE. | | | | |
|---|---|---|---|---|
| | Acceptability limits of overall defect score[1] | | | |
| **Acceptability level** | **Unweighted** (max score 150) | **Weighted** (max score 350) | **Description of acceptability limits** | **Operability limits** |
| A | <30 | <70 | Desirable | Operable |
| B1 | 31 - 48 | 71 - 112 | Undesirable (upper) | |
| B2 | 49 - 66 | 113 - 154 | Undesirable (lower) | |
| C1 | 67 - 108 | 155 - 252 | Unacceptable (upper) | |
| C2 | >108 | >252 | Unacceptable (lower) | Inoperable |

NOTES
1. Limits of acceptability for weighted and unweighted overall classification derived from individual defect acceptability limits (Table 12.3).

## 12.3 Specification Development

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

### 12.3.1 Assessment of Material Property and Performance Relationships

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

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

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

**Table 12.5** Overall Mine Site Functional Performance Classification

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

**Table 12.6** Material Parameter Relationship to Overall Unweighted Functional Performance Classification

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

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

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

**Table 12.7** Material Parameter Relationship to Overall Weighted Functional Performance Classification

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

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

**Table 12.8** Individual Defect Functional Performance Classification

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

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

### 12.3.2 Assessment of TRH20 Specifications in Relation to Performance Ranking

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

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

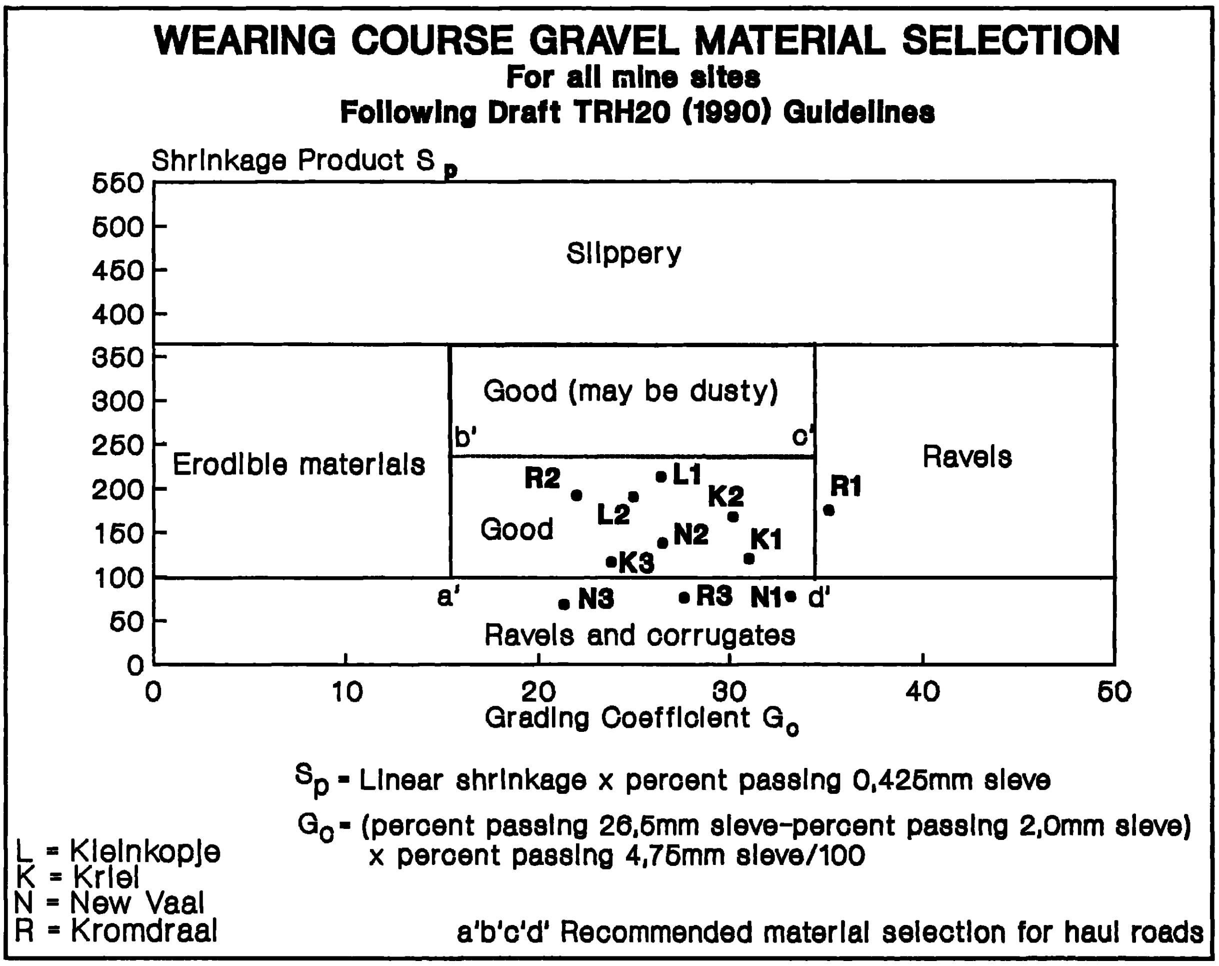


**Figure 12.2** Location of mines sites in terms of TRH20 selection guidelines.

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

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

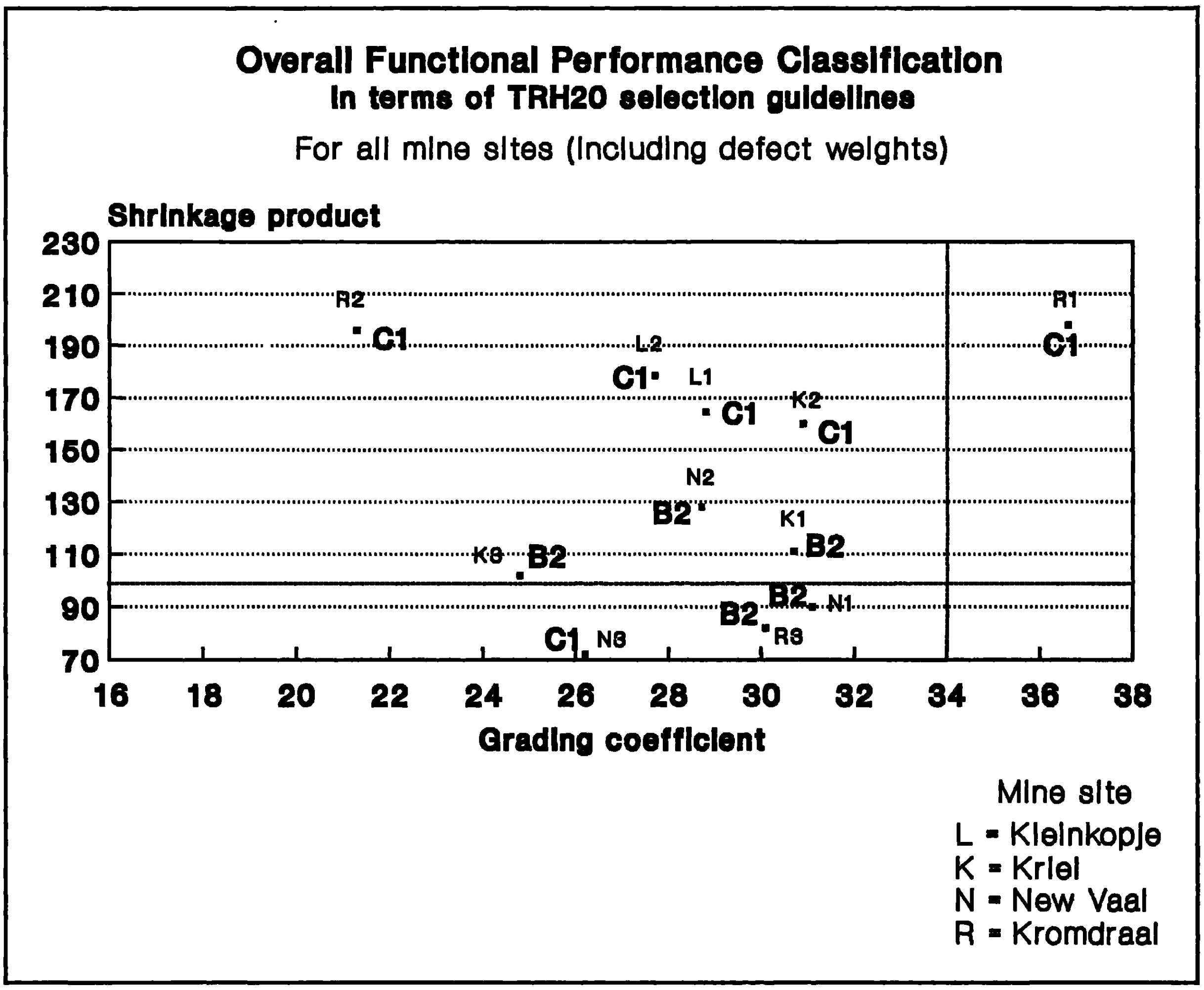


**Figure 12.3** Overall mine site functional performance classification in relation to TRH20 specifications.

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

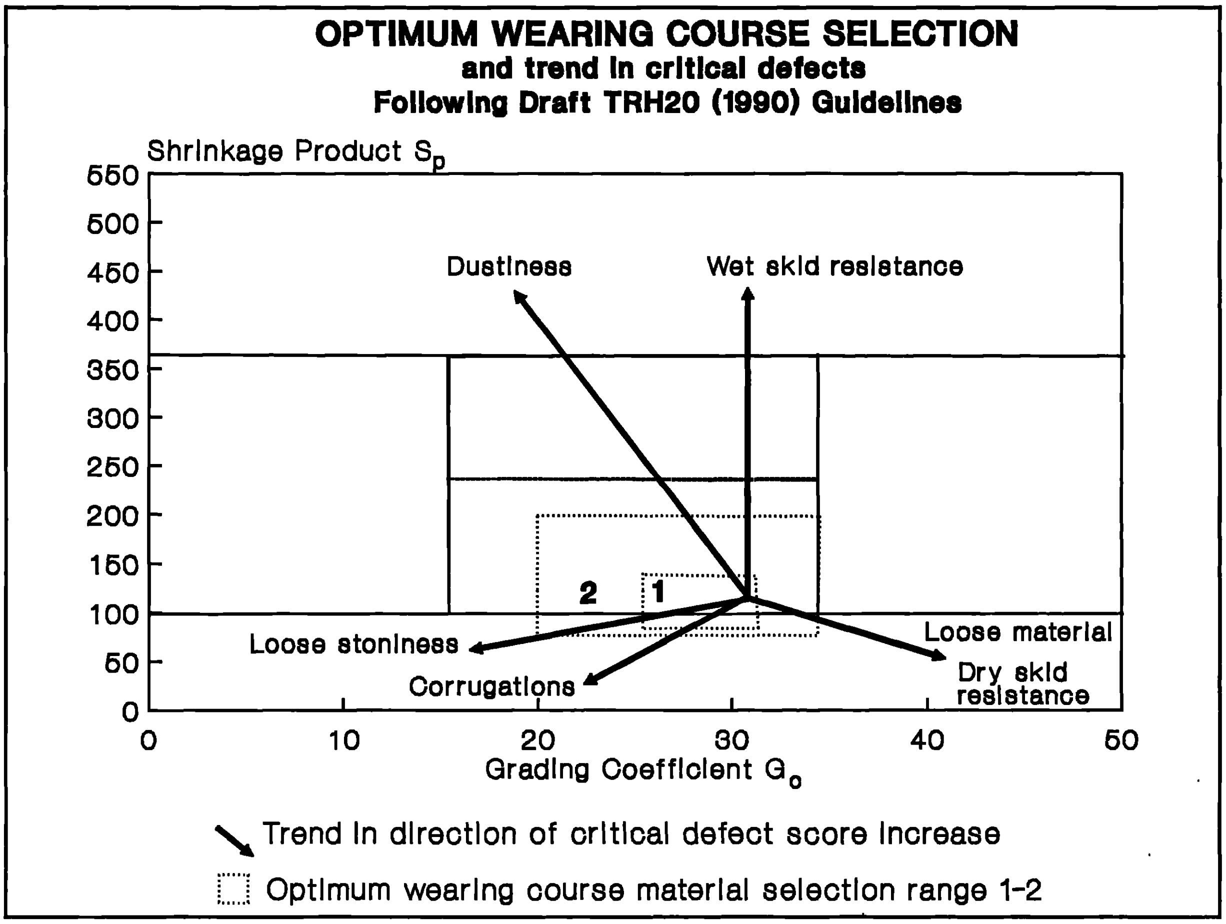


**Figure 12.4** Optimum Material Selection Ranges and General Trends of Increasing Defect Scores.

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

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

## 12.4 Wearing Course Material Selection Guidelines

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

**Table 12.10** Recommended Parameter Ranges for Wearing Course Material Selection

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

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

## 12.5 Summary and Conclusions

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

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

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

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

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

**Notes**

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

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

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

# CHAPTER 13
# ROAD ROUGHNESS PROGRESSION MODEL

## 13.1 Introduction

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

## 13.2 Subjective Evaluation of Road Roughness

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

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

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

SUBJECTIVE EVALUATION OF ROAD ROUGHNESS

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

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

COMMENTS AND OBSERVATIONS

**Figure 13.1** Recording form for subjective haul road roughness evaluation.

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

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

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

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

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

## 13.3 Correlation of Subjective Evaluation of Roughness with IRI

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

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

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

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

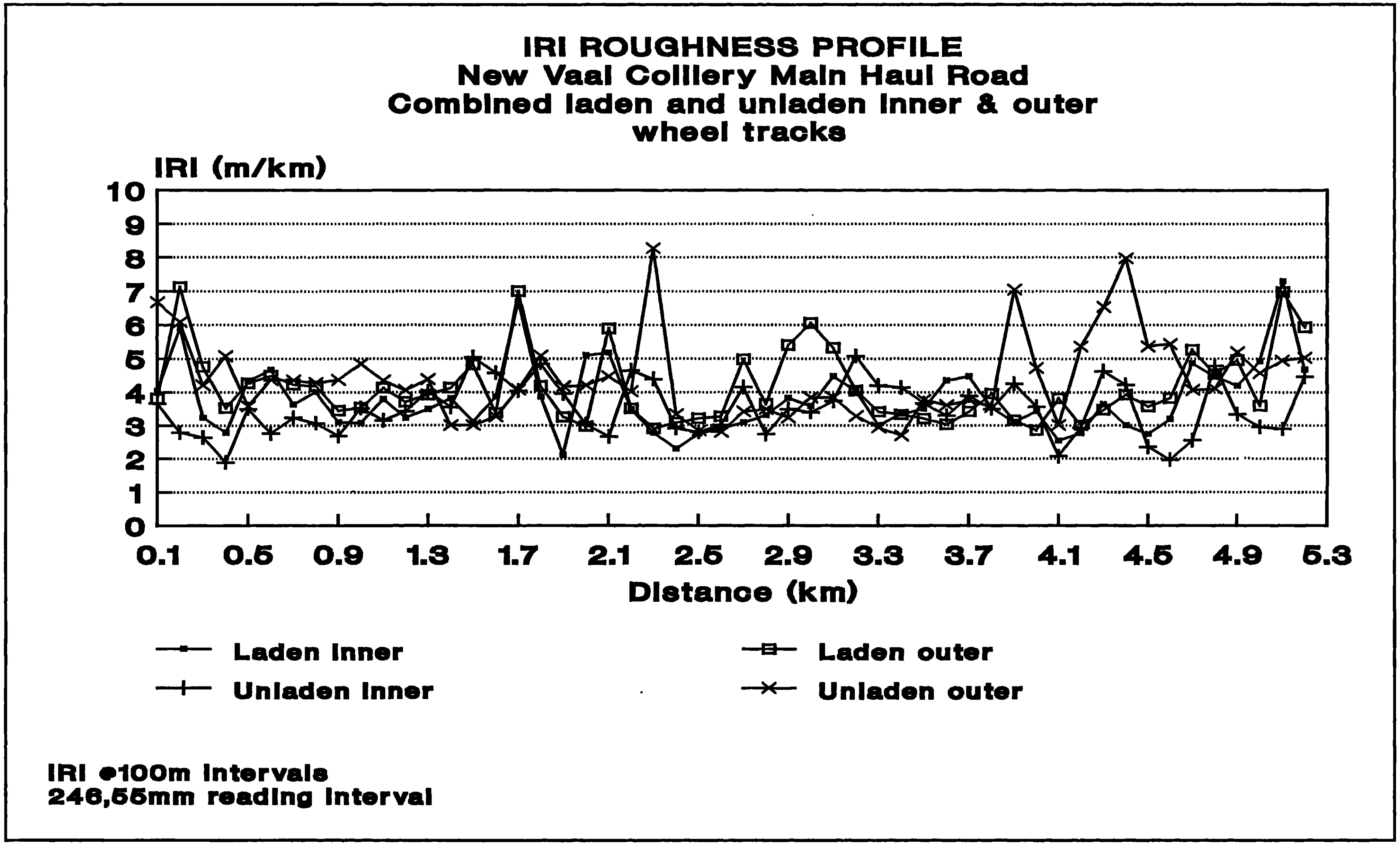


Figure 13.2 Typical IRI roughness profiles for laden and unladen carriageways, inner and outer wheel paths.

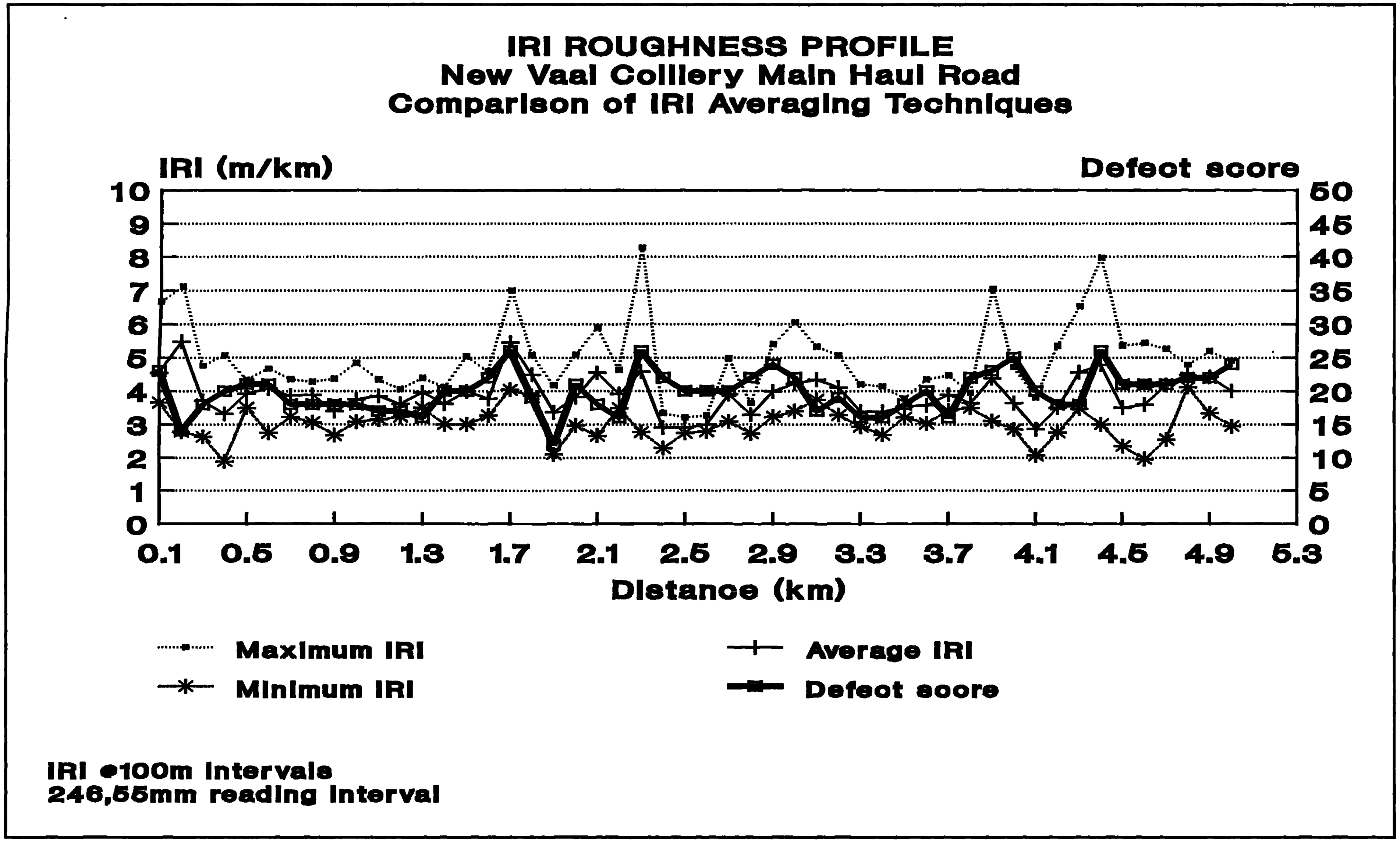


Figure 13.3 Comparison of maximum, average and minimum IRI roughness with roughness defect score

Both are illustrated in Figure 13.4.

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

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

## 13.4 Analysis of Rolling Resistance and Roughness Defect Score Relationship

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

- surface rolling resistance
- air resistance

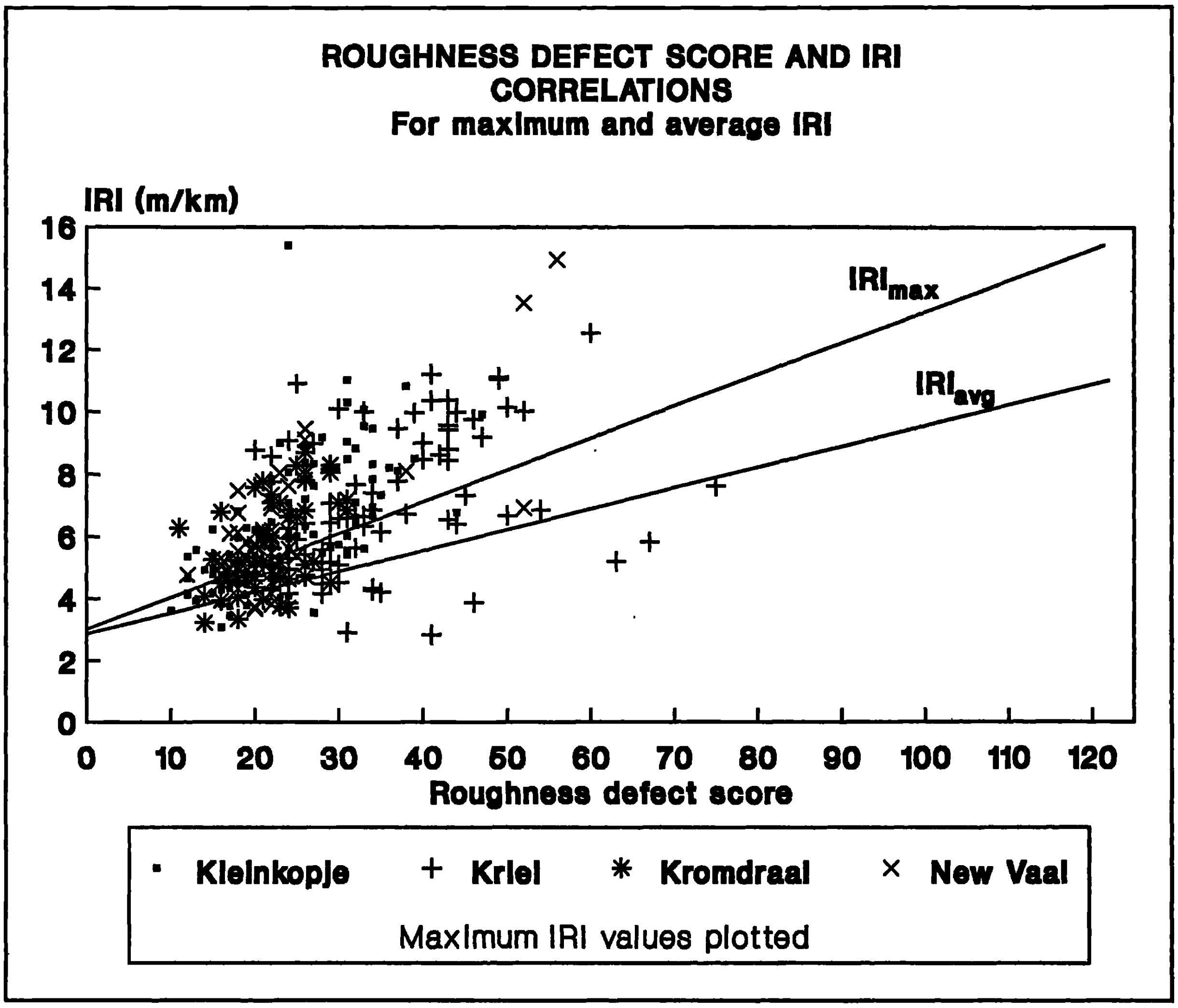


**Figure 13.4** Correlation between IRI and RDS data and model.

**Table 13.3** IRI and Roughness Defect Score Correlation Statistics

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

- gradient resistance
- horizontal curve resistance.

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

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

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

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

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

### 13.4.1 Analytical Approach to Rolling Resistance Measurement

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

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

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

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

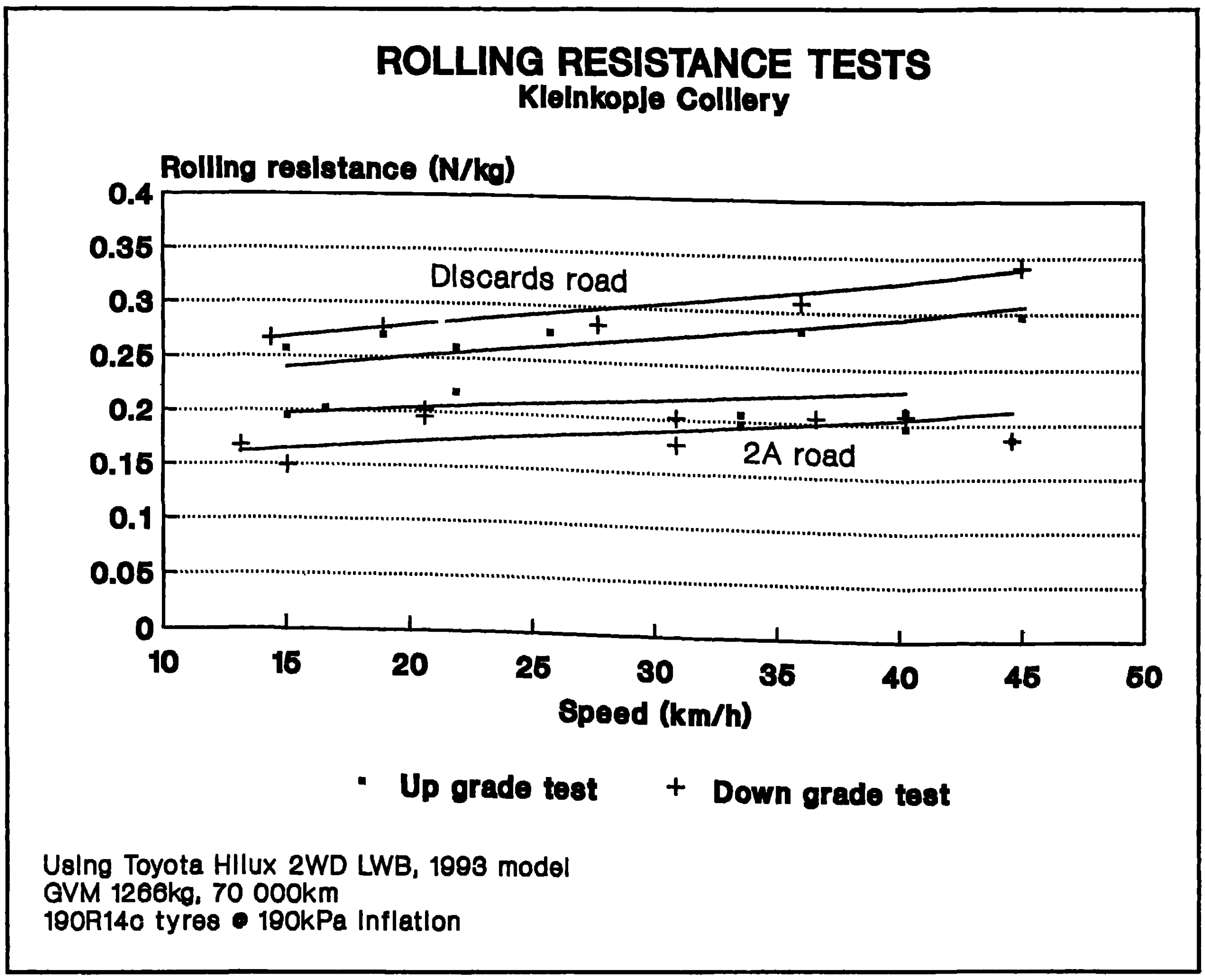


**Figure 13.5** Typical results from rolling resistance tests in up- and down-grade directions from two test sections.

### 13.4.2 Correlation of Rolling Resistance with Roughness Defect Score

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

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

where

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

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

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

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

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

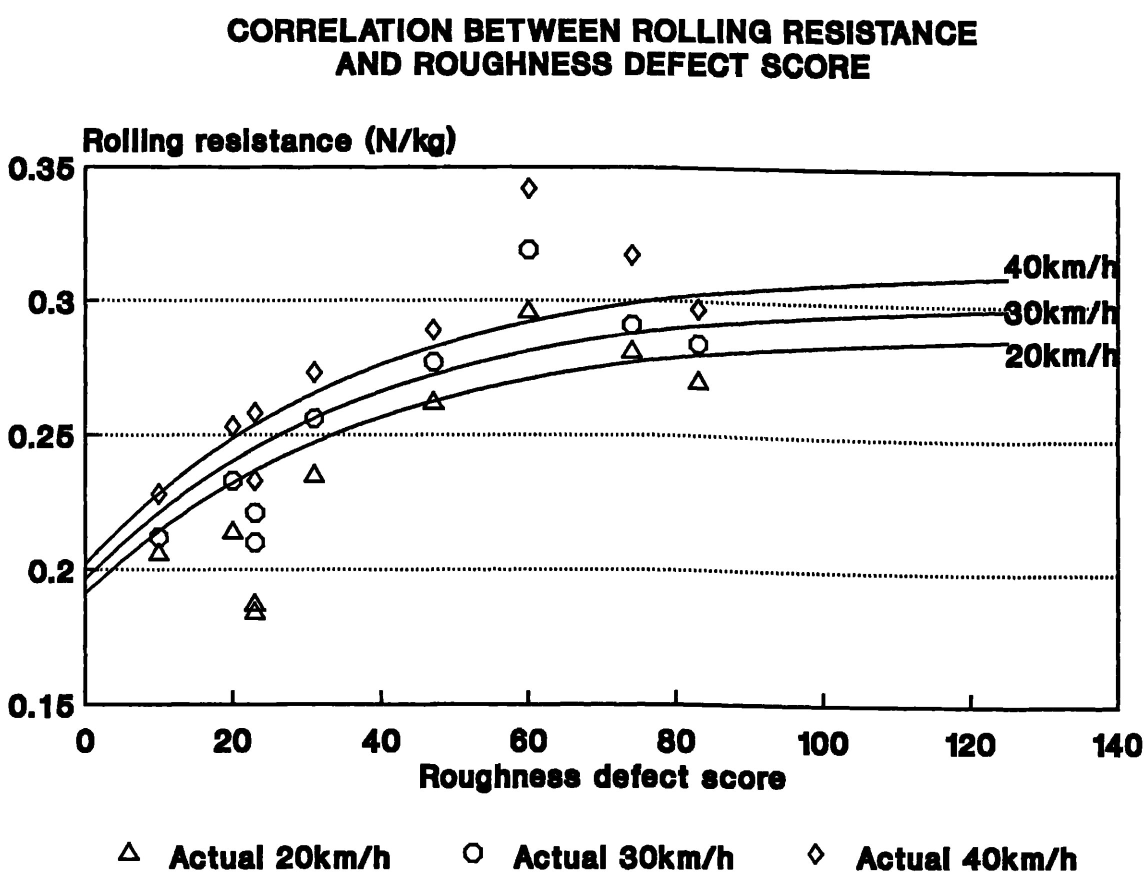


**Figure 13.6** Illustration of correlation between actual and model predicted rolling resistance at 20, 30 and 40km/h.

### 13.4.3 Limits on the Applicability of the Results

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

**Table 13.4** Rolling Resistance and Roughness Defect Score Correlation Model Statistics

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

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

$$CR = 0{,}0128 + 0{,}00061.IRI \tag{13.5}$$

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

$$CR = 0{,}0139 + 0.00026.IRI \tag{13.6}$$

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

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

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

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

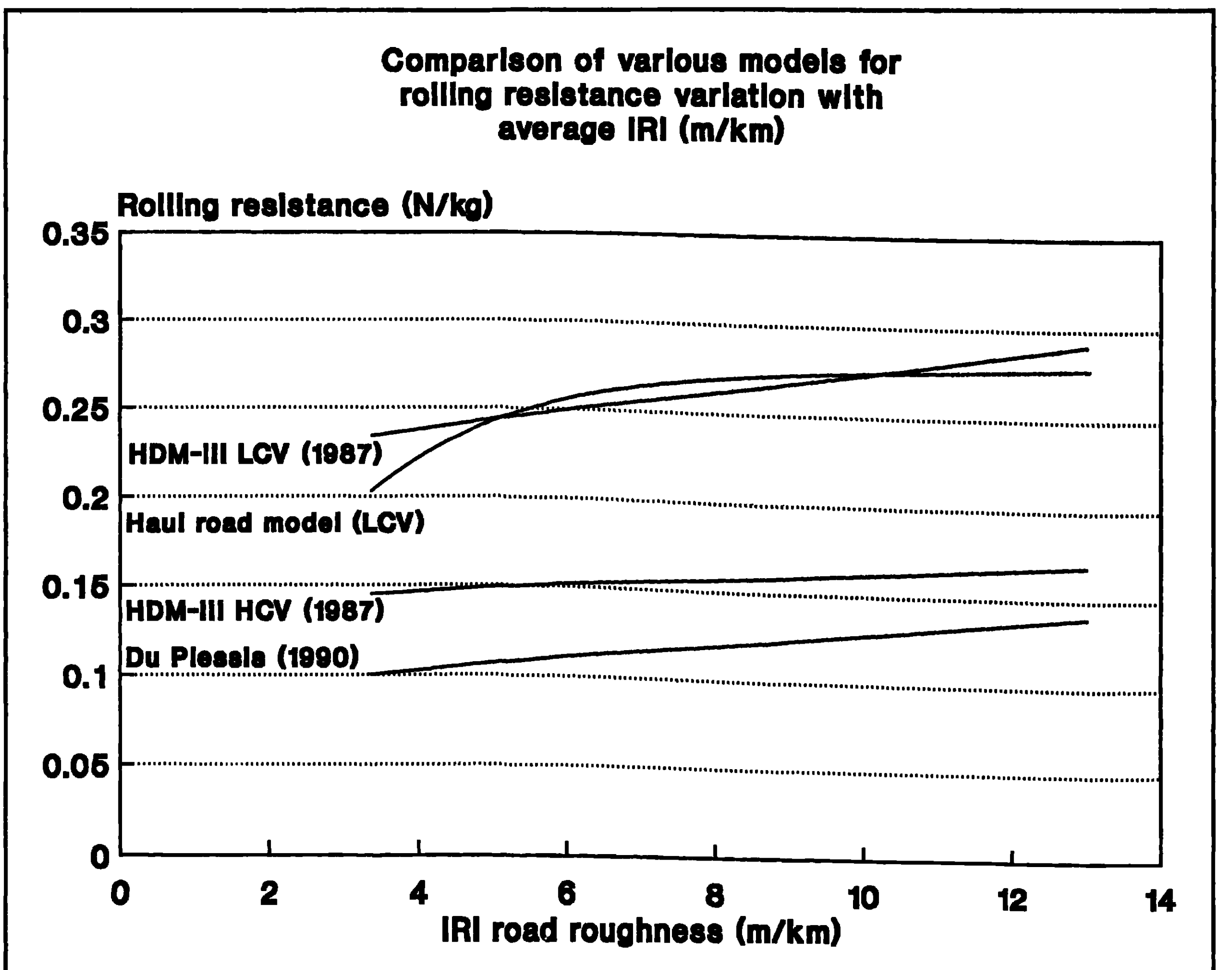


**Figure 13.7** Comparison between models of coefficient of rolling resistance increase with IRI roughness.

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

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

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

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

## 13.5 Road Roughness Progression Model

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

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

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

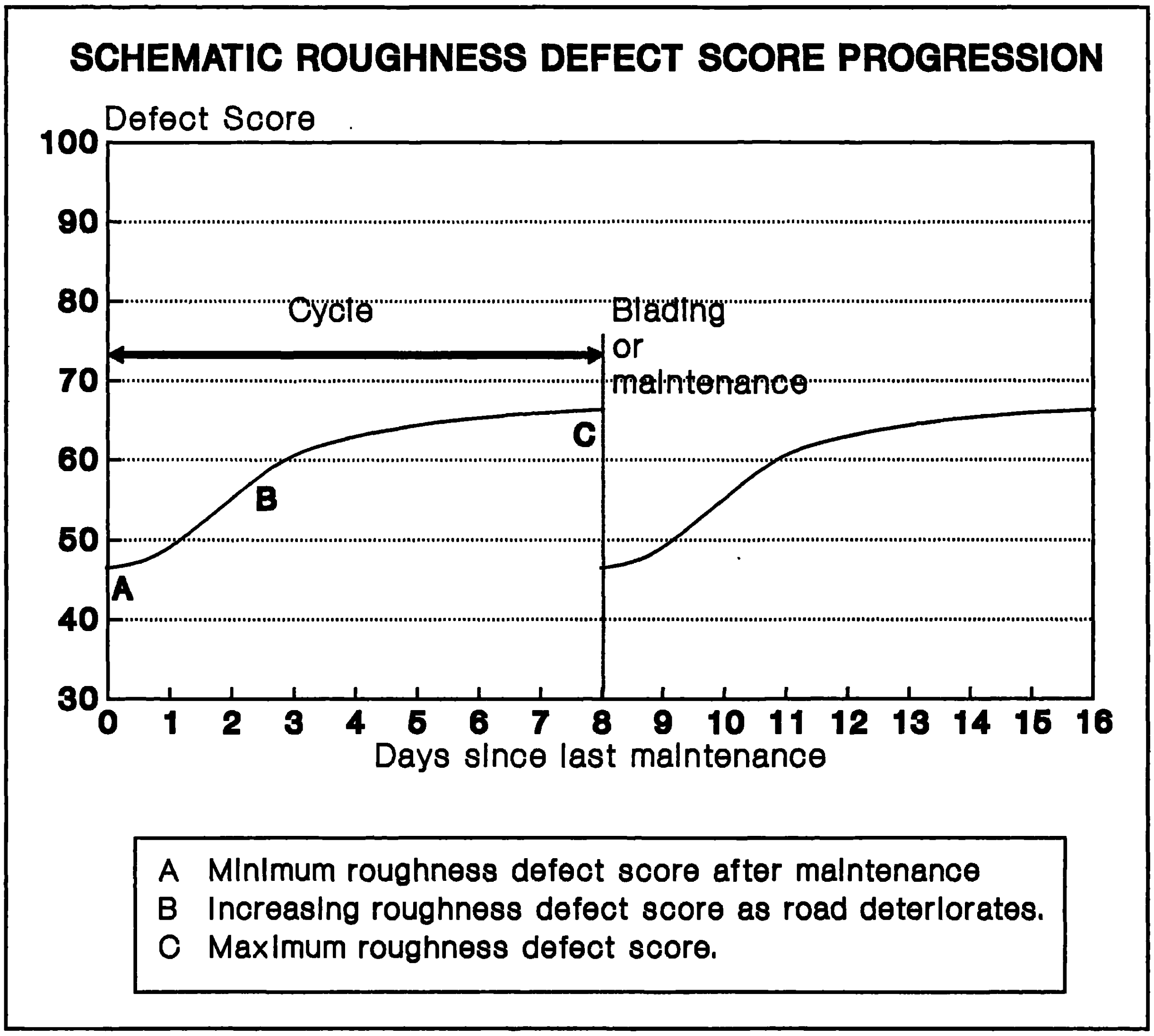


**Figure 13.8** Schematic illustration of roughness defect score model.

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

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

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

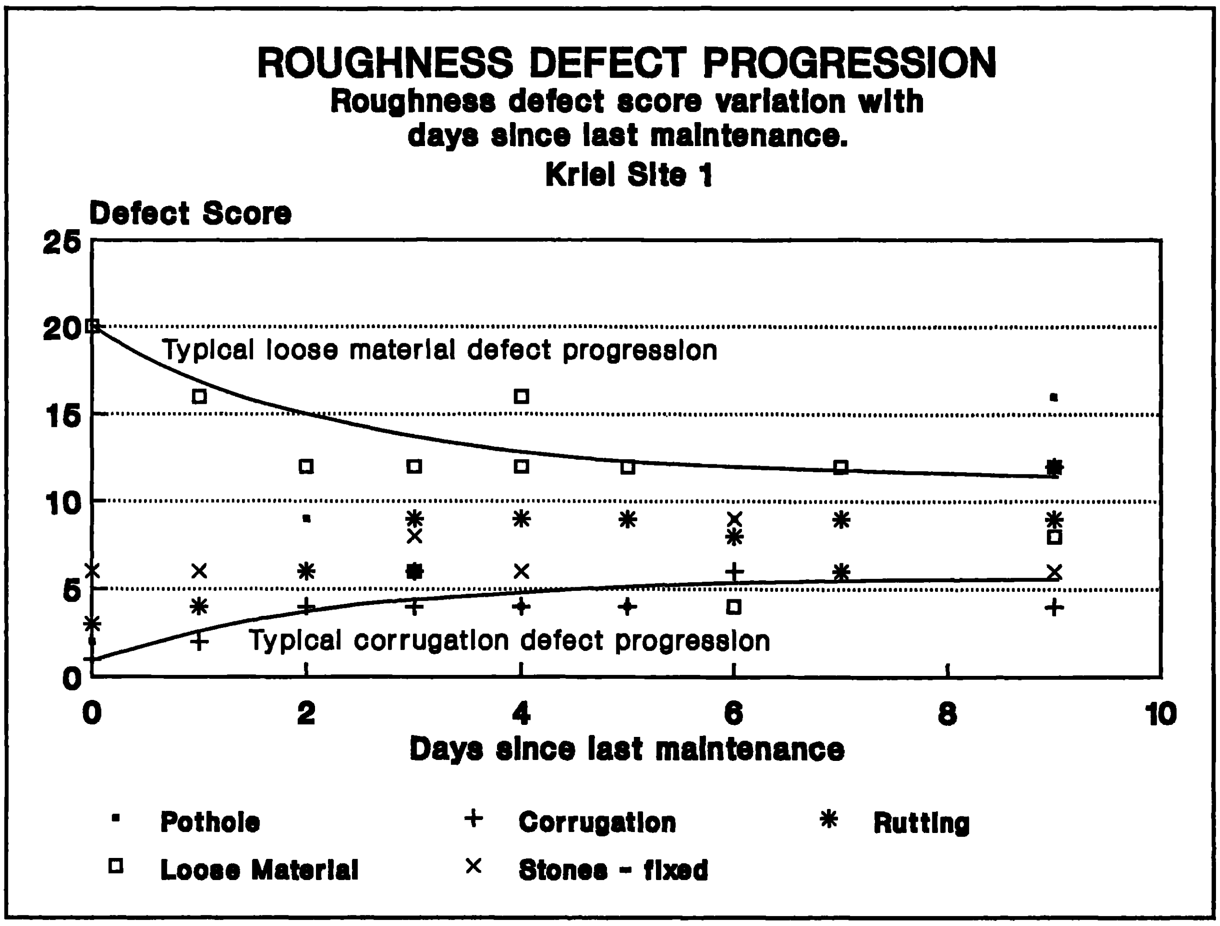


**Figure 13.9** Typical individual roughness defect component score progressions.

where

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

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

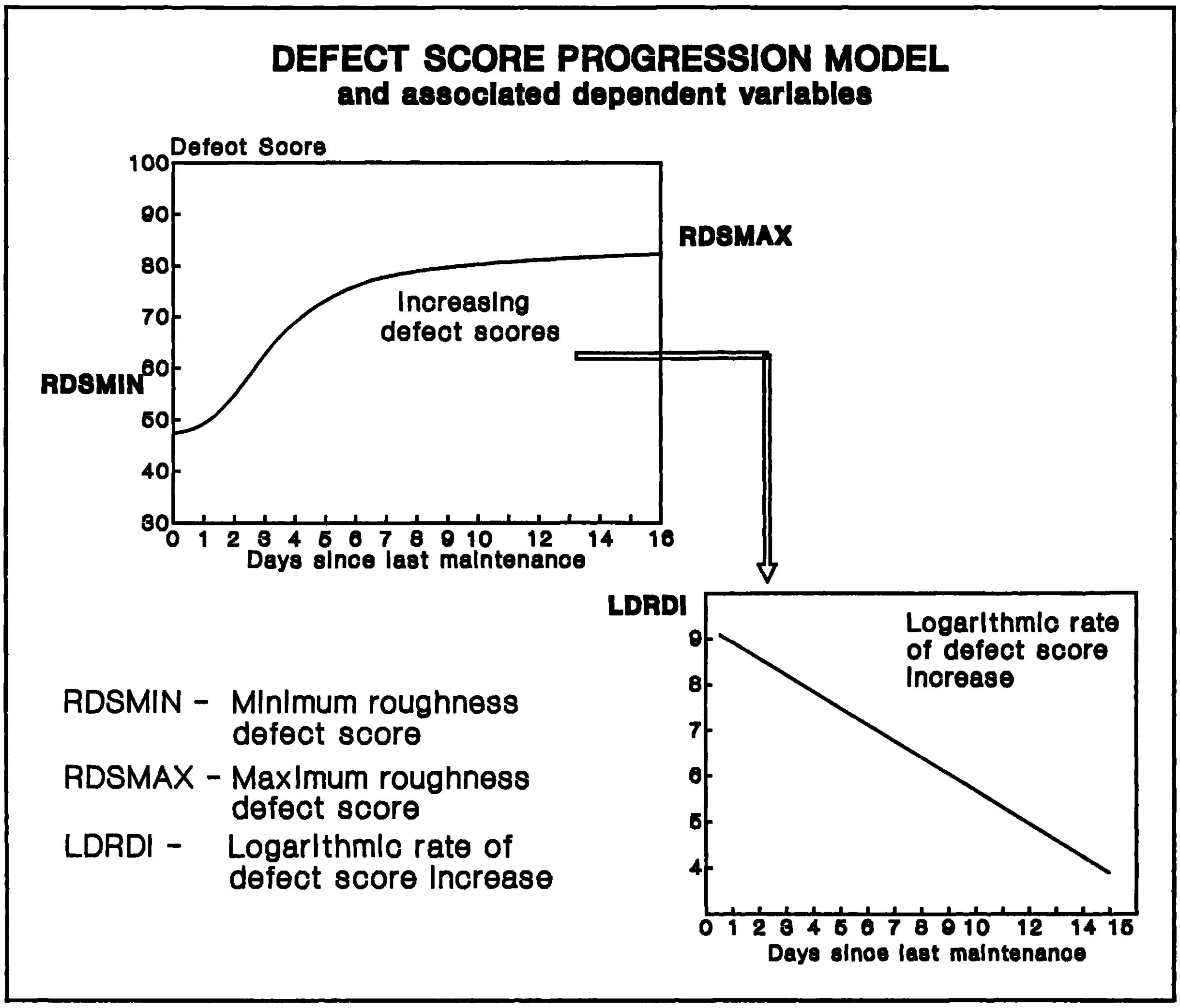


**Figure 13.10** Selection of model and dependant variables for roughness defect score progression.

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

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

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

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

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

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

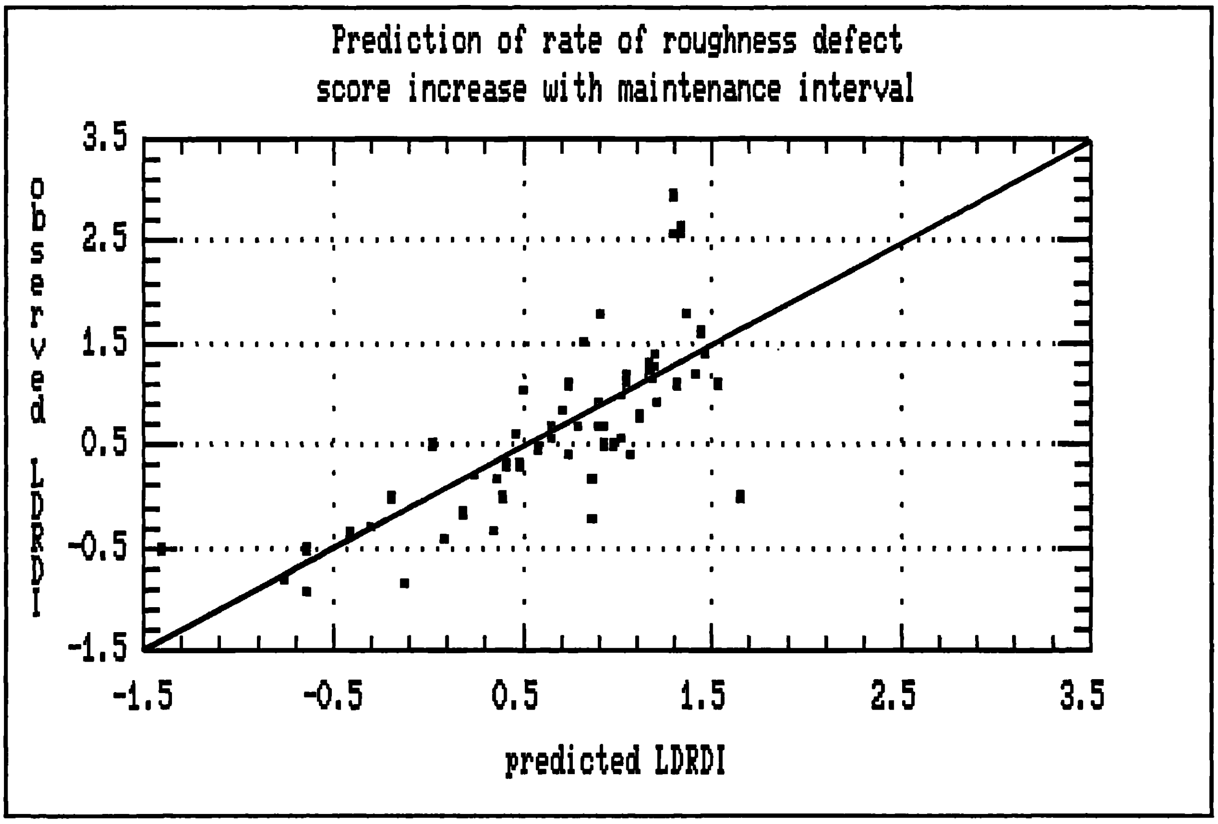


**Figure 13.11** Goodness of fit for model of LDRDI.

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

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

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

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

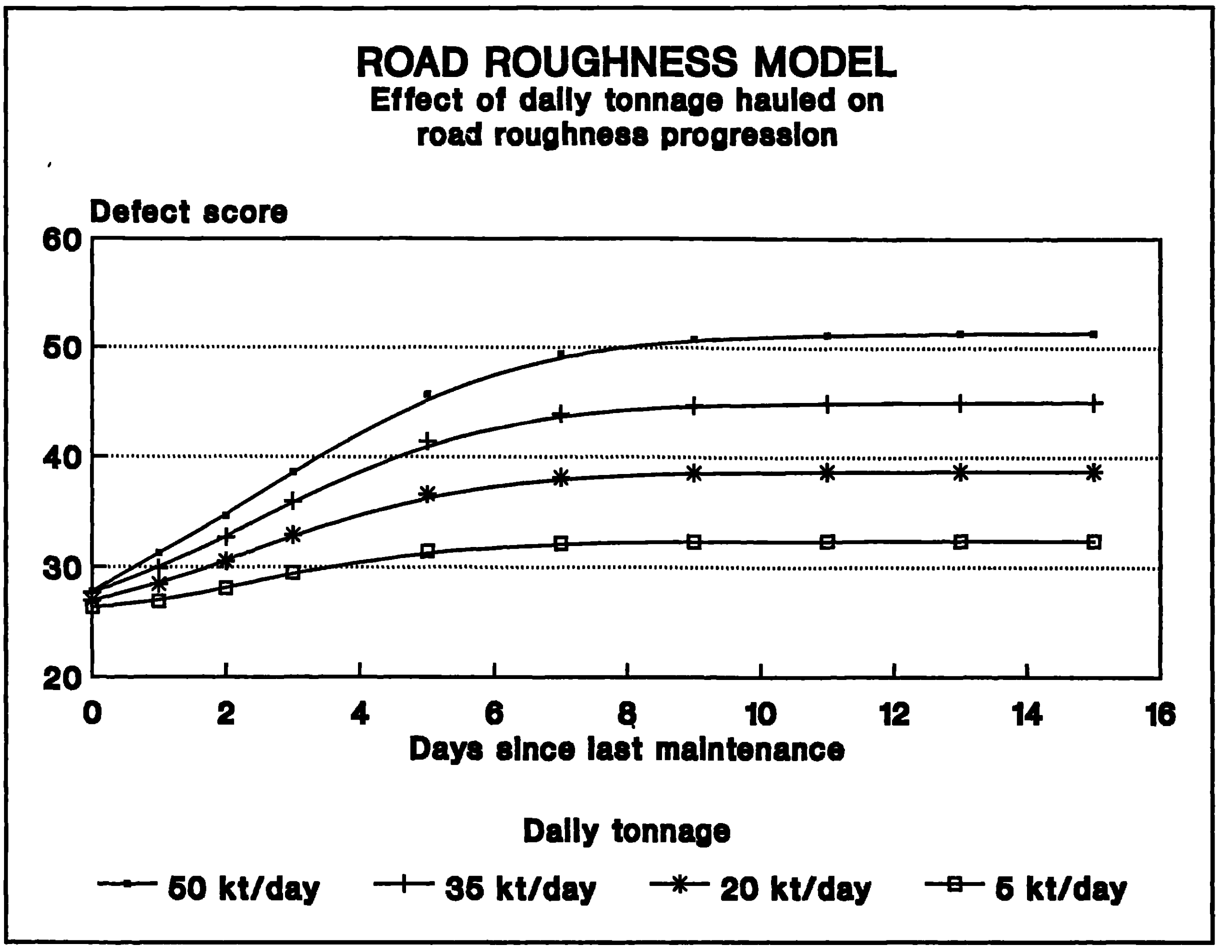


**Figure 13.12** Effect of increasing daily tonnage on roughness defect score progression.

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

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

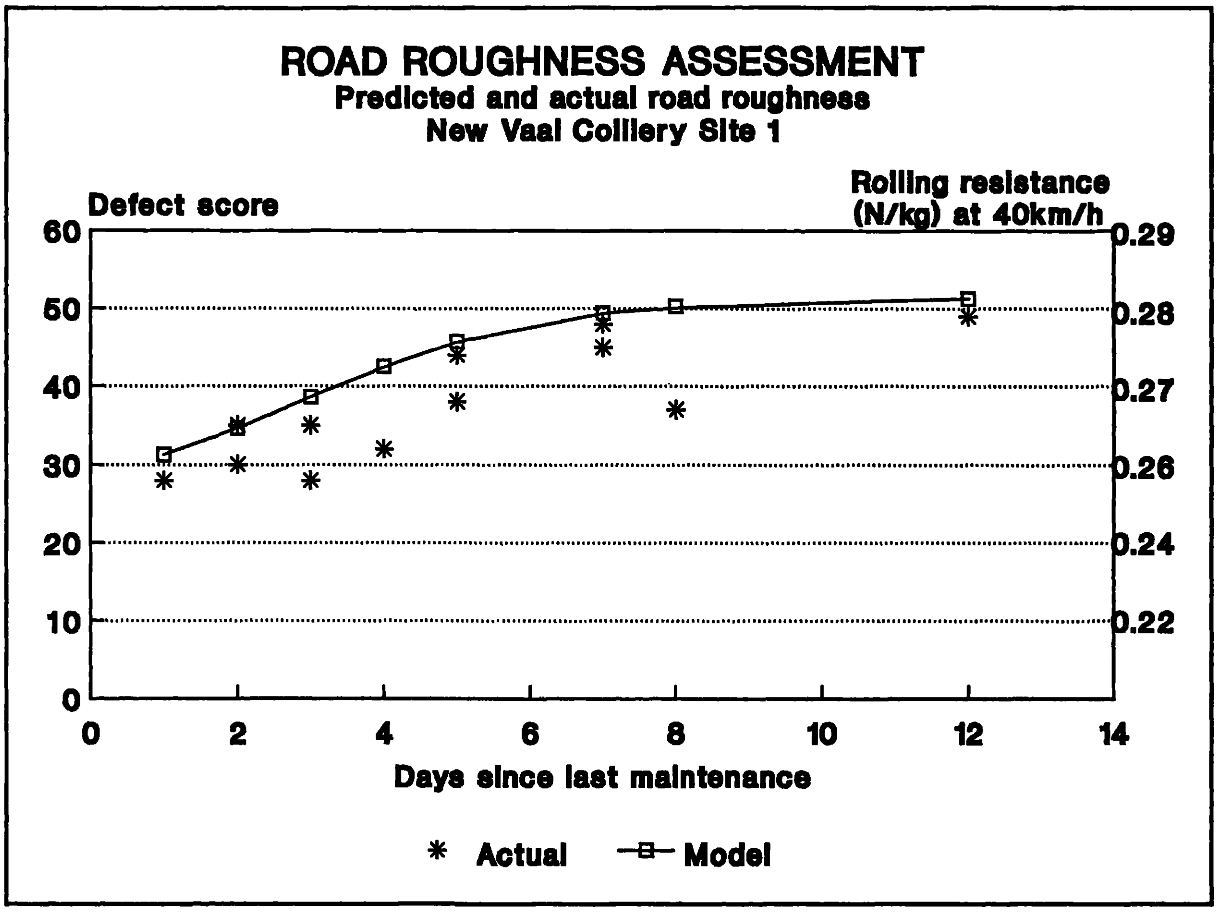


**Figure 13.13** Estimation characteristics of prediction model for roughness progression as applied at New Vaal Colliery site 1.

## 13.6 Summary and Conclusions

A qualitative road roughness evaluation technique was developed as a precursor to the development of a model for roughness progression which forms the basis of the MMS model. The adoption of roughness defect results for pothole, corrugation, rutting, loose material and fixed stoniness from functional monitoring over a 12 month period enabled such a model to be developed based on a maintenance interval of between 1 and 19 days. Increasing traffic volume, grading coefficient and shrinkage product were all associated with an increasing rate of roughness progression whilst increasing CBR and plasticity index were associated with a

**Table 13.5** Roughness Defect Score Progression Model Statistics

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

decreasing progression.

To facilitate portability and comparison of the qualitative assessment technique, the qualitative road roughness was compared to the IRI roughness. Expressions were developed to enable direct comparison to be made between roughness defect score and IRI. In addition, rolling resistance was assessed and results compared to established models for light commercial vehicles. The model derived for mine haul road roughness variation with IRI was found to be broadly similar to models developed for paved and unpaved public roads, albeit with a non-linear rate of change of rolling resistance per unit IRI. Based on the tentative similarity between experimentally derived rolling resistance model values for mine haul road roughness and those reported in the literature it was proposed that the models derived to describe rolling resistance variation with road roughness be provisionally adopted in the MMS model. However, to fully characterise the effect of road roughness attributes on ultra-heavy haul trucks it is recommended that an investigation be undertaken specifically using these trucks since the direct application of the data is nevertheless tenuous.