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DESIGNING AND MANAGING UNPAVED OPENCAST MINE HAUL ROADS FOR OPTIMUM PERFORMANCE

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ABSTRACT

The expansion of surface mining has led to the development of very large off-highway trucks currently capable of hauling payloads in excess of 290t. Mine haul roads have historically been designed empirically, relying heavily on local experience; the trend in increasing truck size will thus render the current pavement systems inadequate. Since truck haulage costs can account for 10%-50% of the total costs incurred by a surface mine, not only would the maintenance costs of existing roads of inadequate design increase, vehicle operating and maintenance costs would also increase prohibitively. There is thus a need for improved design technologies encompassing the construction and management techniques of mine haul roads, appropriate for the wheel loads of vehicles now in use.

The aim of the paper is to present the different components of a mine haul road design and management system and to demonstrate the value of its application through case studies. The system has been applied at several South-African surface mines and distinct benefits have been derived. The improved structural design of a new road resulted in a 29% saving in construction costs and also provided better service, whilst the optimal selection and management of wearing-course materials provided better functionality at lower total transportation operating costs.

INTRODUCTION

Surface mining in South Africa accounts for over 66% of the total run-of-mine tonnage mined. Over 70% of copper, 80% of ferrous metals and 95% or 65 million tons of the land's industrial minerals are mined by surface mines and quarries. In the coal mining industry, over of 40% or 106 million tons run-of-mine coal was produced by opencast methods which require, inter alia, the transport of raw coal from the pit to the loading or transfer point. In any surface mining operation, the transport of ore, and to a lesser extent waste, is accomplished by large haul trucks running on haul roads that have, at best, been empirically designed with little or no recognition of the consequences of inadequate design on cost per ton hauled, operational efficiency or safety. Considering that truck haulage costs can account for up to 50% of the total costs incurred by a surface mine, it is of paramount importance that these costs are minimised. This becomes all the more critical as tonnage increases and larger haul trucks are deployed. Not only do the maintenance costs of existing roads of inadequate design increase, vehicle operating and maintenance costs also increase prohibitively.

The operating performance of a pavement can be subdivided into three distinct design categories as defined in Figure 1. In addition to the mechanical engineering challenges involved in the design and construction of large dump trucks, specific mining engineering problems arise, primarily as a result of the gross vehicle mass (GVM) and the resultant loading applied to the pavement. Taking a typical example of a 180t capacity rear dump truck, the GVM of 317t results in a maximum dual wheel axle load of 2 086kN. In comparison, public road authorities in South Africa currently permit a legal maximum dual wheel axle loading of 90kN.

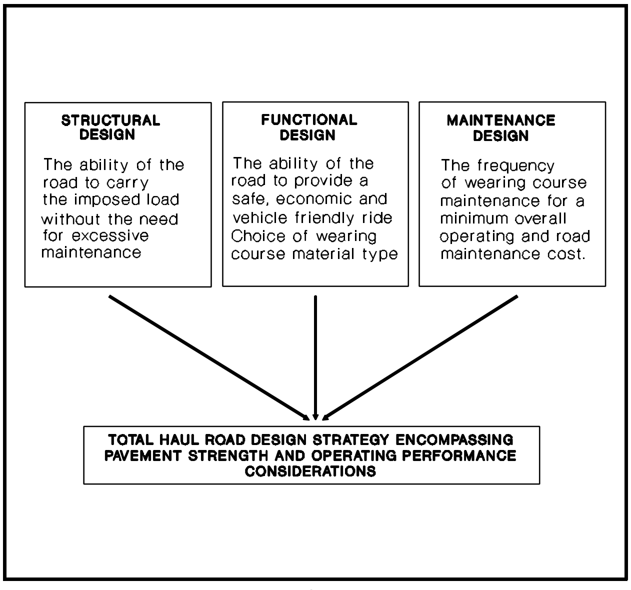

Figure 1 Three Components of a Total Haul Road Design Strategy

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

The maintenance aspect of haul road design cannot be considered separate from the structural and functional design aspects since the two are mutually inclusive. Design and construction costs for the majority of haul roads represent only a small proportion of the total operating and maintenance costs. Whilst it is possible to construct a mine haul road that requires no maintenance over its service life, this would be prohibitively expensive, as would the converse but rather in terms of operating and maintenance costs. An optimal functional design will include a certain amount and frequency of maintenance (watering, grading etc.) and thus maintenance can be planned, scheduled and optimised within the limits of required road performance and minimum vehicle operating and road maintenance costs. The major problem encountered when analysing maintenance requirements for haul roads is the subjective and localised nature of the problem; levels of functionality or serviceability being user- and site-specific. No guidelines exist concerning maintenance management and scheduling for specific levels of functionality, nor the cost implications thereof, both in terms of vehicle operating and road maintenance.

Geometric design refers to the layout and alignment of the road, in both the horizontal (curve radius, etc.) and vertical (incline, decline, ramp gradients, cross-fall, super-elevation etc.) plane, stopping distances, sight distances, junction layout, berm walls, provision of shoulders and road width variation, within the limits imposed by structural, functional and maintenance design parameters. The ultimate aim is to produce an optimally efficient and safe geometric design and considerable data already exists pertaining good engineering practice in geometric design, suffice to say that an optimally safe and efficient design can only be achieved when sound geometric design principles are applied in conjunction with the optimal structural, functional and maintenance designs (Thompson et al, 1997). Therefore by addressing the structural, functional and maintenance design problems, an integrated haul road design strategy combining mine layout, construction techniques, available material and road maintenance equipment with hauler choice was developed to optimise a particular mining situation.

The aim of this paper is to summarise the improved haul road design and management techniques which have been developed specifically for surface mines. A new mechanistic structural design methodology is presented which can reduce construction cost and improve the structural strength of the pavement. The improved functionality of a pavement is addressed in terms of the optimum selection of wearing course materials, based on road-user acceptability criteria. Finally, the concept of maintenance management, in which an optimal maintenance strategy is sought which minimises both road-user and road maintenance cost elements is addressed in terms of the various cost models required to evaluate such a system and the typical cost-benefits associated with its adoption.

HAUL ROAD STRUCTURAL DESIGN

Mine haul roads deteriorate with time due to the interactive effort of traffic load and specific subgrade material strengths and structural thicknesses. Vertical compressive strains induced in a pavement by heavy wheel loads decrease with increasing depth which permits the use of a gradation of materials and preparation techniques; stronger materials being used in the upper regions of the pavement. The pavement as a whole must limit the strains in the sub-grade to an acceptable level and the upper layers must in a similar manner protect the layers below. Using this premise, the road structure should theoretically provide adequate service over its design life.

In an attempt to obtain satisfactory service over a road's design life, pavement design models can be used to predict performance over a wide range of traffic loads and road structural designs. Pavement structural design is the process of developing the most economical combination of pavement layers (in relation to both thickness and type of materials available) that is commensurate with the in-situ material and traffic to be carried over the design life. Typical pavement design terminology is shown in Figure 2.

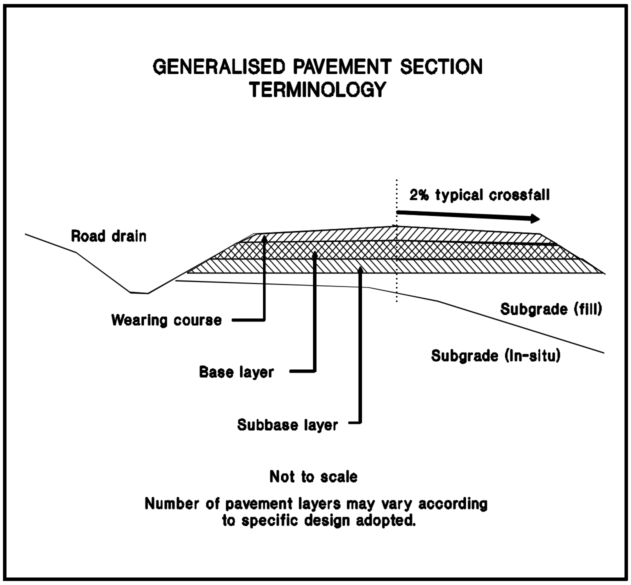

Figure 2 Haul Road Structure Terminology

In general terms, applied load, subgrade strength and the pavement structural thickness and layer strength factors predominantly control the structural performance of a haul road. The approach adopted in determining a suitable mechanistic structural design involved the quantification of the factors given above for existing haul roads to determine the efficacy of the various design options. To fully characterise the structural performance of existing or future designs of haul roads, each factor was analysed at various levels using a designed factorial experiment. Whilst only the principal developments resulting from this work are presented, further details are given by Thompson and Visser (1996).

Empirical Structural Design Techniques

The findings of a United States Bureau of Mines (USBM) study (Kaufman and Ault, 1977) were that haul road structural design techniques were entirely empirical, mine operators often electing to forego the use of sub-base materials and accept infringements on mobility in the interest of economics. The USBM work was one of the first annotated applications of the California Bearing Ratio (CBR) cover thickness design technique for mine haul roads.

The CBR method (Boyd and Foster, 1950) has been widely applied to the design of mine haul roads. The CBR method of haul road design was based on empirical results relating to the design of asphalt-surfaced airfield pavements for wheel-gear loads up to 4 400kN. When aggregate-surfaced mine haul roads are considered in conjunction with stabilised bases, albeit at similar load levels, the same approach is of questionable validity. Recourse to a mechanistic analysis was found necessary to quantify the extent of any over- or under-design inherent in the CBR approach since the latter technique cannot assess each layer independently in terms of its load bearing capacity. If a single pavement layer is assumed, the technique can be used to generate reliable estimates of total cover over in-situ material, but where multi-layer structures are involved and the optimal design is sought, a mechanistic approach is more appropriate (Thompson and Visser, 1998).

South African Mechanistic Design Method

The South African Mechanistic Design Method (SA-MDM) is based on a theoretical model of pavement layer response parameters (stresses, strains and deflections in each layer) by assuming a linear-elastic multi-layer system. Empirically derived limiting design criteria are then used with which to assess the pavement under the specific loading conditions, thereby determining the level of service and in turn, the time at which some maintenance or rehabilitation would be required. The method has been applied mostly to the design of asphalt pavements on public roads (South African Roads Board, 1994).

Recommended Mechanistic Structural Design Technique

The assessment of existing empirical structural design guidelines for mine haul roads indicate that a mechanistic approach to structural design would be more appropriate. A number of mine roads previously assessed using the empirical approaches were comparatively assessed using a mechanistic approach. Pavement deflection profiles generated from Multi-depth Deflectometer installations in these pavements were analysed with the aid of the ELSYM5A computer program, the results of the multi-layer linear elastic analyses were then used to deduce acceptable design criteria for haul road structural design. A structural performance categorisation was used as a guide to the efficacy of the various existing haul road designs. Strains generated from the multi-layer elastic solution for the particular road test section were then compared with the structural performance categorisation to established suitable design criteria.

Two design criteria were proposed with which to assess the structural performance of mine haul roads, namely factor of safety (FOS) for the two uppermost layers and vertical elastic compressive strain for each layer below the top layer. The vertical strain criterion correlated well with structural performance; those mine sites exhibiting poor performance and an associated excessive deformation/maximum deflection were seen to be associated with large vertical compressive strain values in one or more layers. From an analysis of the data it was evident that an upper limit of 2000 microstrain should be placed on layer strain values. Strain values exceeding this value were shown to be associated with unacceptable structural performance. The depth of influence at which load induced stresses are no longer felt was identified at approximately 3000mm pavement depth. The absence of deflections below this depth may be ascribed to the low stresses induced in the in-situ material.

The FOS did not appear to correlate with the structural performance classification and it was concluded that the FOS design criteria in the upper layers is not applicable to haul road structural design. In the absence of any definitive criteria, a 200mm layer of compacted (95-98% Mod. AASHTO) good quality gravel (G4-G5 following Committee of State Road Authorities TRH14, 1985) would appear most appropriate, based on those mine sites where wearing course layers exhibited adequate structural performance.

The strains induced in a pavement are a function of the effective elastic modulus values ascribed to each layer in the structure. In order to facilitate mechanistic design of mine haul roads, some indication of applicable modulus values was required. This was achieved by considering the individual layer modulus values generated by the mechanistic analysis of existing pavements and comparing these values to established modulus values and the associated material classification. Pavement layers comprised generally a G4-G6 gravel or low quality gravel where local mine ferricrete is used and a modulus range of 150-200MPa was proposed for these gravels when used as a wearing course and 75-100MPa for the same material when used as a base or sub-base layer. Values for the modulus of the in-situ sub-grade material are very much site and material specific and the use of Dynamic Cone Penetrometer (DCP) (Kleyn et al, 1982) derived CBR values in conjunction with published data provided the most tractable approach to ascertaining suitable modulus values for this material. Table I relates the recommended elastic modulus values for granular and in-situ materials comprising the pavement layers. To facilitate the choice of suitable modulus values for in-situ materials, the associated range of CBR values (derived from DCP probing) and abbreviated specifications are given.

Recommendations regarding the structural design of surface mine haul roads are centred on the inclusion of a dumprock layer within the structure. This design is based upon the findings of the mechanistic analysis of roads which incorporate a stabilised layer. This effect can be adequately reproduced by using mine dumprock or parting material in place of the stabilised layer. The optimal location of this layer is immediately below the wearing course layer, thereby reducing deflections (and consequent deformation) in the lower layers to a minimum. Using this approach, a reduced structural thickness was realised without the attendant deformation and reduction in structural performance level that would otherwise be evident without a rock layer. Figure 3 shows a comparison between the recommended mechanistically-derived optimal design and that derived from the empirical CBR-based cover-curve design approach, based on an in-situ material modulus value of 85MPa, a 429kN dual rear wheel load and a 630kPa contact stress. It is clear that the optimal mechanistic design reduces damaging vertical compressive strains to below the critical 2000 microstrain limit and is also associated with reduced material volumetric and compaction requirements.

A cost comparison compiled from contractor tender unit costs for the construction of a road designed according to the empirical CBR cover curve technique and one constructed according to the mechanistically derived optimal design was undertaken to ascertain if any cost advantage was associated with the mechanistic design. The variable costs taken into account were those of the volume and area of materials required and the associated costs of placing and compaction. An equivalent cost of the optimal mechanistic design was calculated from the actual construction costs of the CBR-based design. It was found that a 29% variable cost saving was realised, by virtue of the reduced material volumetric and compaction requirements associated with the mechanistic optimal design. In terms of total construction cost (including preliminary and general costs) a 17% total cost saving was realised. Subsequent to this analysis several roads were constructed according to the mechanistic design and during an extremely wet 1996 summer, superior performance was reported, compared with the existing roads.

Table I Suggested Modulus Ranges for Granular Materials

Material Code[2]	Abbreviated Specification[5]	Recommended Effective Elastic Modulus (E) MPa [1]		
		Over granular layer	Wet state (good support)[3]	Wet state (poor support)[4]
G1	Dense-graded unweathered crushed stone. Max size 37,5mm. 86-88% of apparent density. Fines PI<4	150	50-250	40-200
G2	Dense-graded unweathered crushed stone. Max size 37,5mm. 100-102% Mod AASHTO. Fines PI<6	100-400	50-200	40-200
G3	Dense-graded stone and soil binder. Max size 37,5mm. Min 98% Mod AASHTO. Fines PI<6	100-350	50-150	40-200
G4	Natural gravel base, CBR≥80, PI≤6	75-350	50-150	30-200
G5	Gravel CBR≥45, PI≤10, max size 63mm	40-300	30-200	20-150
G6	Gravel, low quality sub-base. CBR≥25. Max size < **b** layer thickness	30-200	20-150	20-150
In situ[6]	CBR≥25		135	105
	24≥CBR≥15		125	85
	14≥CBR≥10		120	65
	9≥CBR≥7		95	55
	6≥CBR≥3		65	45

Notes

1.	Using a Poisson's ratio of 0,35	2.	Following CSRA TRH14 (1985) classification
3.	In-situ material (dry state)	4.	In-situ material (wet state)
5.	Using soaked CBR values	6.	Using CBR values at in-situ density

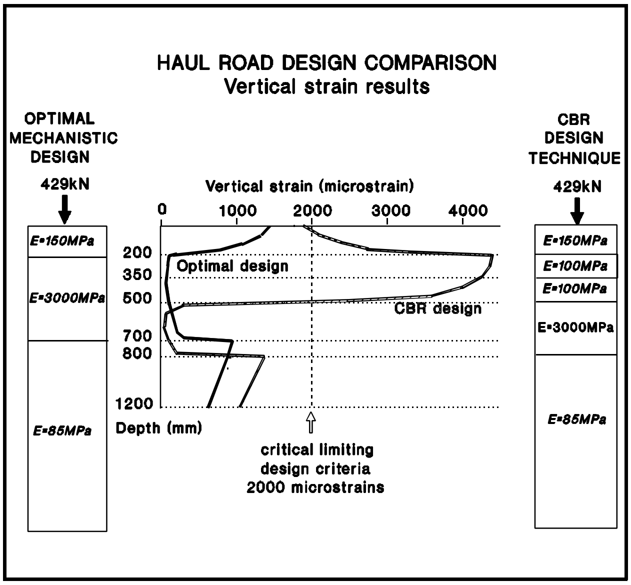

Figure 3 Results in Terms of Vertical Strain Design Criteria for CBR and Mechanistic Optimal Designs

HAUL ROAD FUNCTIONAL DESIGN

The functional trafficability of a pavement is dictated to a large degree through the choice, application and maintenance of wearing course materials. Poor functional performance is manifest as poor ride quality, excessive dust, increased tyre wear and damage and an accompanying loss of productivity. The corollary of these effects is seen as an increase in overall vehicle operating and maintenance costs.

Previous work on functionality was found to be highly subjective and localised in nature (Thompson, 1996) and it was thus necessary to develop a qualitative functional performance assessment methodology in which typical functionality defects could be classified and ascribed a defect score in terms of extent and degree (severity) of a defect. The defects of potholing, corrugating, rutting, loose material, dustiness, fixed and loose stoniness, longitudinal, slip and crocodile cracking, erosion and skid resistance were evaluated monthly in terms of degree of severity and extent. In addition, the maintenance interval was also recorded to enable predictions to be made concerning the rate of overall and individual defect functional performance deterioration with time and traffic. This approach reduced subjectivity and, by virtue of the degree and extent classifications, provided a universal basis for the assessment and reporting of functionality.

The experimental approach adopted in determining suitable material selection guidelines involved the analysis and quantification of a range of factors which determine the efficacy of the various wearing course material types, in terms of functionality. In general, these factors are the material type itself, together with road geometrics, climate and traffic volumes. To fully characterise the functional performance of existing or future selections, each factor was analysed at various levels by means of a designed factorial experiment.

From the statistical analysis of deterioration and maintenance effects, a defect progression model was derived from consideration of the rate of change in overall defect score over a maintenance cycle. The model incorporated wearing course material properties, especially grading and plasticity parameters, together with traffic volume. By analysing the rate of change of individual defect score beyond a minimum value encountered at each site, models were developed for the rate of change in defect score with time and the propensity of specific material properties to affect the progression. In determining suitable wearing course material selection guidelines this work confirmed qualitative observations that grading and plasticity parameters will adequately anticipate the functional performance of a wearing course material.

In parallel with a functional performance assessment exercise carried out at a number of mine sites, a functionality acceptability questionnaire was completed by mine and equipment suppliers to indicate the performance levels required by operators, again, according to the qualitative functional performance assessment methodology. Each functional defect was ascribed a range of scores in terms of degree and extent covering desirable, undesirable and unacceptable performance, as illustrated in Figure 4. This enabled a comparison to be made between the functionality of the various types of wearing course material surveyed. In addition to assigning acceptability ranges to each type of defect, the impact and accident potential of each defect was categorised and ranked according to the total impact and accident potential on the components of hauling, namely operation, truck and tyre. It was clear from the ranking exercise that wet skid resistance, dustiness, erodibility and ravelling and corrugating are critical defects which control the functionality of mine haul roads. An understanding of the functional consequences, in terms of the possible generation of these defects, was therefore incorporated into the selection criteria established for mine haul road wearing course materials.

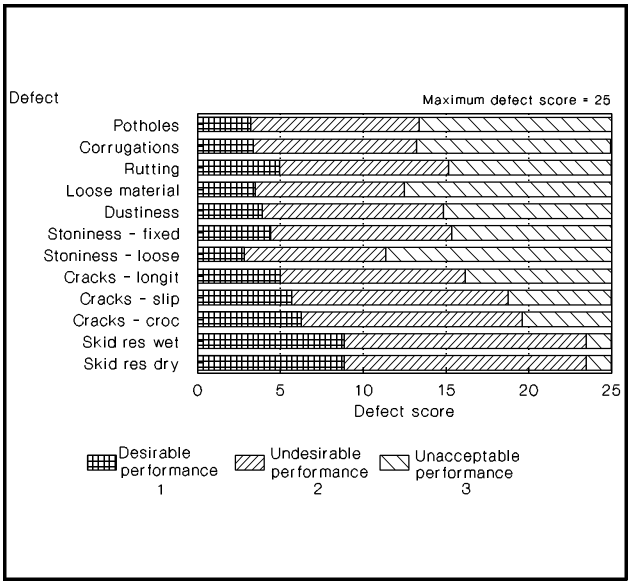

Figure 4 Limits of Defect Functional Performance Acceptability

Recommended Wearing Course Material Selection Guidelines

The derivation of wearing course material selection guidelines was based on the identification, characterisation and ranking of haul road functional defects, together with an assessment of the suitability of existing wearing course material selection guidelines and classifications as a basis for mine haul road material specification. 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 parameter ranges represented by typical haul road construction materials.

The TRH20 (CSRA TRH20, 1990) wearing course material selection guidelines were found to be a more suitable source for the specification of mine haul road wearing course material parameter requirements. A revised range of parameters was derived based on the road-user preference for much reduced wet slipperiness, dustiness and dry skid resistance defects, as shown in Figure 5. The specification included the parameters of shrinkage product (S_p) and grading coefficient (G_c) and limits of 85-200 and 20-35 respectively were proposed. In addition, from analysis of the range of material property parameters assessed and their association with the functional defects analysed, additional parameter ranges were specified as given in Table II. By analysing the trends evident in the individual defect rankings, the predictive capability of the specification was enhanced by depicting the variation in functional defects which would arise when departures are made from recommended parameter limits. In addition, by incorporating material property values into the defect score progression models, operators can determine the practical implications of using a sub-standard wearing course material or blend of materials, in terms of their impact on overall haul road functionality, individual defect scores and acceptability, together with the required maintenance interval for user-defined functionality defect score upper limits.

Wearing Course Performance Improvement Through Dust Palliation

Since the wearing course material selection guidelines include a predictive component, the practical implications of using sub-standard wearing course materials can be assessed and the anticipated functional defects pro-actively managed. Most mines source wearing course materials from local borrow-pits and very little control can be exercised over the quality of these materials. Dustiness is a common and critical defect on most mine haul roads, effecting safety, productivity and total operating costs (Thompson, 1996, Amponsah Dacosta, 1998). Using the limits of dust defect desirable performance (as shown in Figure 4), should a particular wearing course material exhibits an undesirable or unacceptable dust defect, a direct quantitative

Table II Recommended Wearing Course Material Parameter Specifications for Optimal Functional Performance

WEARING COURSE MATERIAL SELECTION PARAMETERS			
Material Parameter (following CSRA TRH20, 1990)	**Range** **Min**	**Max**	**Impact on Functionality**
Shrinkage Product	85	200	Reduce slipperiness but prone to ravelling and corrugation
Grading Coefficient	20	35	Reduce erodibility of fine materials, but induces tendency to ravel
Dust Ratio	0,4	0,6	Reduce dust generation but induces ravelling
Liquid Limit (%)	16	26	Reduce slipperiness but prone to dustiness
Plastic Limit (%)	12	17	Reduce slipperiness but prone to dustiness
Plasticity Index	4	9	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

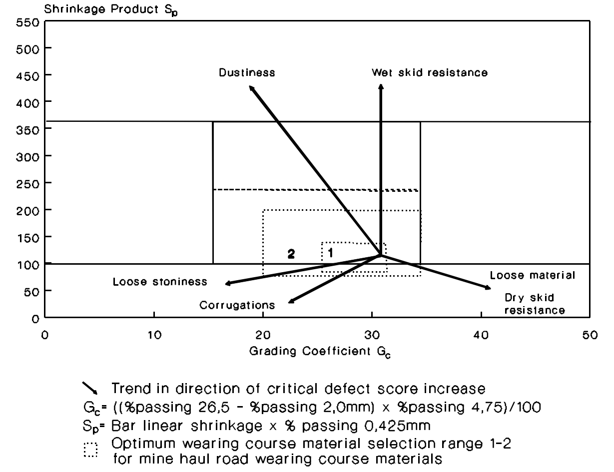

Figure 5 Optimum Material Selection Ranges and General Trends of Increasing Defect Scores

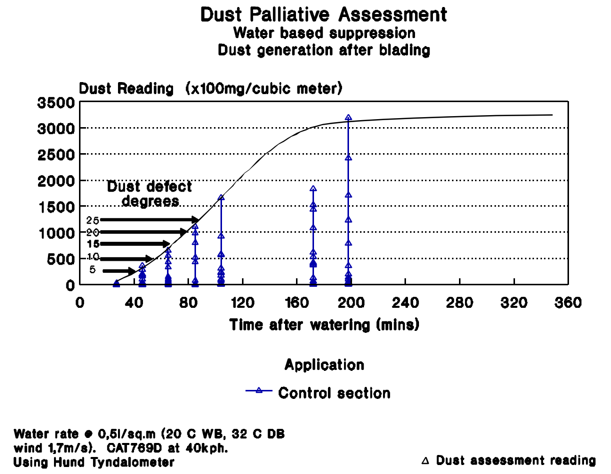

Figure 6 Increase in Road Dustiness (x100 mg/m^3 minus 10µm dust) Following a Single Application of 0,5l/m^2 Water

cost-based comparison can be made between the various dust management solutions; water-based dust suppression, palliative-based dust suppression or that acheived through the use of a more appropriate wearing course material or mix of materials.

Typical results are presented based on a test program embarked upon by Pennzoil Products (SA) (Pty) Ltd and a local mining company (Thompson and Visser, 1998(a)). In order to provide the mine with quantitative data regarding the efficacy of the dust palliative tested (PennzSuppress® D spray-on mixtures), the mine assessed its own dust defect intervention level score (maximum desirable dust defect score as shown in Figure 4). Figure 6 illustrates the typical increase in dustiness (x100 mg/m^3 minus 10µm dust) as measured with a Hund Tyndalometer on the mine haul road, following a single application of 0,5l/m^2 water, and its correlation to dust defect score. Given the mine's preference for a maximum dust defect score of 15, water spraying of the haul road was thus required every 70 minutes.

By monitoring the performance of a palliated test section, similar quantitative data was generated and the degree of dust palliation and its variation with time and traffic volume was found. A suppression efficiency was determined by comparing the palliated test section suppression performance to the dust suppression acheived by water spraying alone. For the particular combination of palliative treatment, traffic volume and type, climatic conditions and wearing course material type, suppression efficiencies of over 200% were maintained for up to 15 days following application as shown in Figure 7. This performance was correlated with the maximum (allowable mine) dust defect score of 15 and a palliative performance model derived. This indicated that re-treatment of the road was required every five days for a palliative and water mix, compared to every 70 minutes with water alone. Further cost-benefits were hypothised based on the reduced loss of fine (binding) materials, reducing the need for periodic re-gravelling, reduced road maintenance intervals, reduced vehicle operating costs and a reduction in visibility and health hazards on the road. Testwork is currently in progress to develop models of dust suppression efficiencies for a range of treatments, wearing course material types and traffic volumes, by means of which operators can determine the cost-effectiveness of

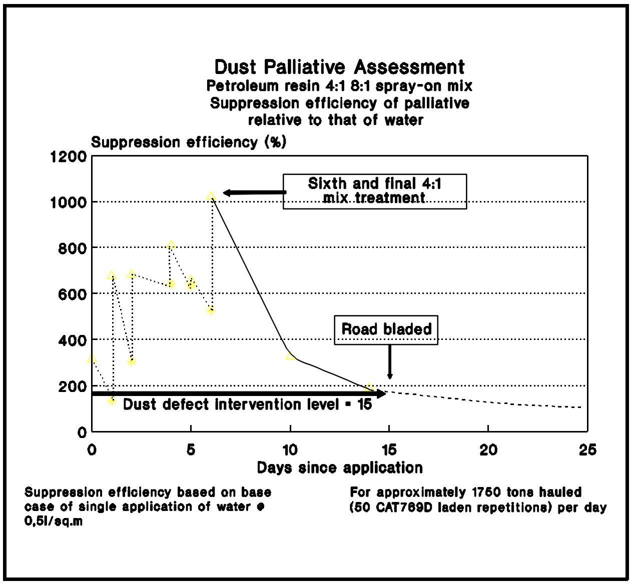

Figure 7 Typical Suppression Efficiency Curve and Comparison with Mine Maximum Allowable Dust Defect Score of 15

such treatments for their own particular combination of circumstances.

HAUL ROAD MAINTENANCE SCHEDULING AND MANAGEMENT

Maintenance design concerns the optimal frequency of wearing course maintenance commensurate with minimum vehicle operating and road maintenance costs. Through the development of a maintenance management system (MMS), the optimum maintenance frequency for a mine haul road network can be determined, commensurate with the lowest total vehicle operating and road maintenance costs. Existing MMS's are based on the optimisation of these elements, as shown schematically in Figure 8.

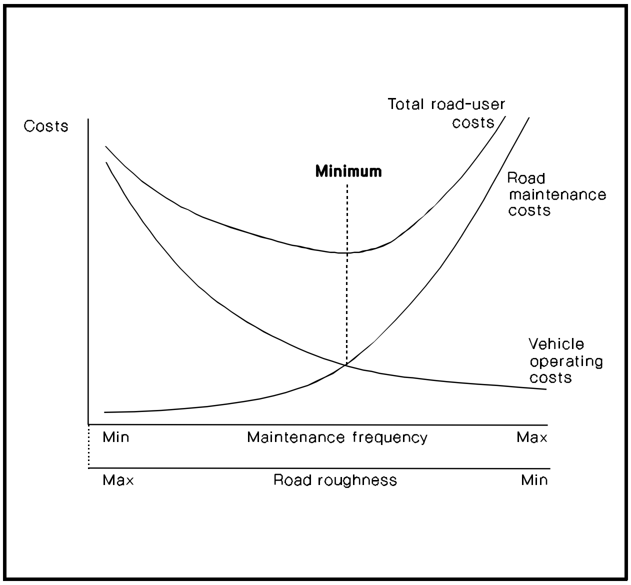

Figure 8 Minimisation of Road Maintenance and Vehicle Operating Costs

Additionally, by combining the functional design recommendations within a MMS, new specifications for wearing course materials or mixes of materials may reduce vehicle operating costs and maintenance requirements, as illustrated in Figure 9 in which the reduced defect scores and rate of deterioration in functionality between the original and optimum wearing course material selection are seen. In order to quantify this cost benefit, the road maintenance and vehicle operating costs (VOC) associated with existing wearing courses were assessed and compared to those estimated from models.

Vehicle Operating and Road Maintenance Cost Models

Two elements form the basis of the economic evaluation, namely pavement roughness (rolling resistance) progression and vehicle operating and road maintenance costs. The proposed mine haul road MMS was developed from established MMS applied on public roads, together with specific modifications which reflect the requirements of mine haul road-users. The road roughness progression model forms the basis of the MMS since roughness (or rolling resistance) is the principal measure of pavement condition that can be directly related to both VOC and the frequency of maintenance activities. A qualitative road roughness evaluation technique was developed, based on the functional assessment methodology of defect degree and extent, as a precursor to the development of a model for roughness progression. The progression model was found to be a function of wearing course material parameters, traffic volumes and maintenance interval. To facilitate portability and comparison of the qualitative assessment technique, expressions were developed to enable direct comparison to be made between roughness defect score, the International Roughness Index (m/km IRI) and rolling resistance (N/kg vehicle mass).

The second element of a MMS for mine haul roads was based on models of the variation of vehicle operating and road maintenance costs with road roughness. VOC models included fuel, tyre and maintenance cost and labour. For the fuel consumption model, simulations were conducted from which four universal equations were derived by means of which vehicle speed could be predicted for any combination of total road rolling resistance and truck loading.

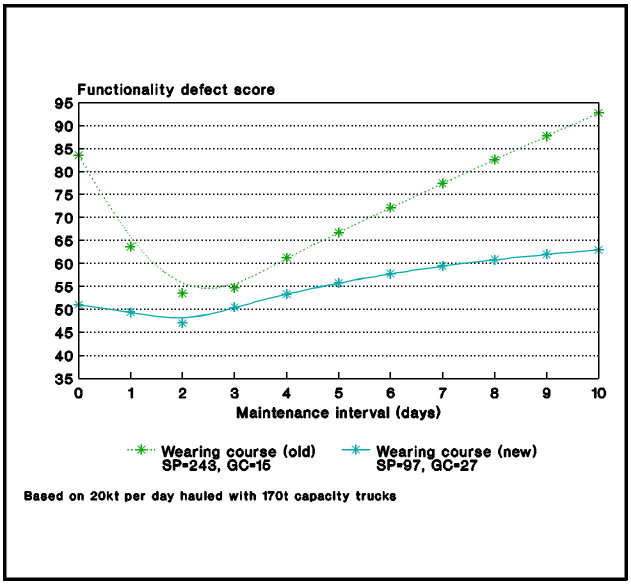

Figure 9 Predicted Reduction in Haul Road Functional Defects for Existing (old) and Optimised (new) Wearing Course Material

With regard to the tyre, vehicle maintenance parts and labour models, existing models developed for public commercial trucks were used as a basis for the development of mine haul truck models (Chesher and Harrison, 1987). Although the parameter ranges bore little resemblance to those of mine haul trucks, when coupled with a hypothesis of the influence road roughness and geometry on these cost components, a basic model was developed in each case. These models were then compared with the limited mine data available to verify the order of magnitude of the costs modelled and, more critically, to indicate the likely rate of change of these costs with road roughness or rolling resistance. These models are discussed in more detail by Thompson and Visser (1996(a), 1997).

MMS Computer Model

The interaction and influences of the various models proposed to represent VOC, road maintenance costs and the progression of road roughness can only be effectively analysed using a systems analysis approach as shown in Figure 10.

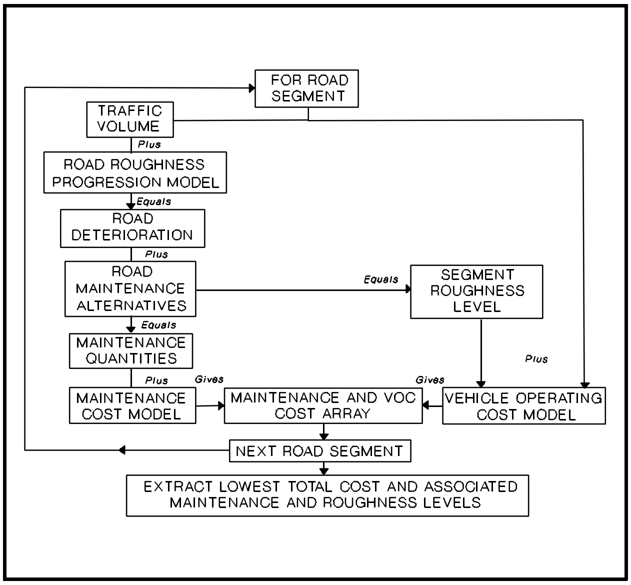

Figure 10 Flow Chart of Proposed MMS for Mine Haul Roads (for a single maintenance strategy iteration)

The MMS model program for mine haul roads was developed to evaluate alternative maintenance intervals and the associated effect on total road-user costs, comprising vehicle operating and road maintenance cost elements. Road maintenance costs and fleet productivity was assessed by means of user specified data in conjunction with a basic grader productivity model. An evaluation of the total cost variation with maintenance interval enabled the optimum maintenance interval to be determined, both on a minimum total road-user cost basis and in terms of maintenance equipment available operating hours. When analysing the results of individual mine simulations, the actual mine operating practice was seen to closely resemble that predicted by the model, especially with regard to increased maintenance interval on lightly trafficked roads. A typical result is illustrated in Figure 11 from which it is seen how total vehicle operating costs for two sections of a mine haul road network are minimised at the optimal road maintenance frequency interval.

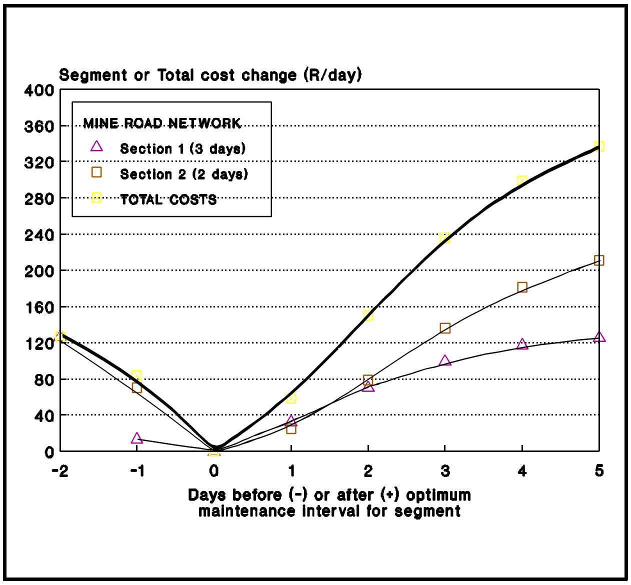

Figure 11 Segment and Total Road-user Cost Variation with Maintenance Interval

Cost savings associated with the adoption of a maintenance management approach are dependant on the particular hauling operation, vehicle types, road geometry and tonnages hauled, etc. From an analysis of the rate of change in vehicle operating and road maintenance costs for individual segments of one particular mine road with reductions in the frequency of maintenance beyond the optimal maintenance interval, these sub-optimal maintenance strategies were seen to be associated with in excess of R310 000 annual over-expenditure on total road-user costs. The adoption of the MMS model program for mine haul roads has the potential to generate significant cost benefits when used dynamically, in conjunction with production planning, to optimise mine haul road maintenance activities for particular combinations of wearing course material, traffic volumes and vehicle types.

CONCLUSIONS

The world-wide expansion of surface mining has led to the development of very large off-highway trucks currently capable of hauling payloads in excess of 290t. Typical axle loads ranging from 110t to 200t are applied to haul roads that have been, at best, empirically designed on the premise of "satisfactory" or "failed", both in terms of structure and function of the road. The use such ultra-heavy haul trucks on surface mines, in conjunction with the current empirical mine haul road design techniques have been shown to be inadequate; not only do the maintenance costs of existing haul roads of inadequate structural or functional design increase, vehicle operating and maintenance costs also increase prohibitively. Under these conditions the need for improved technologies encompassing the construction and management techniques of flexible mine haul roads, appropriate for the wheel loads of vehicles now in use was recognised. Whilst the research was based on South African road construction materials and climatic conditions, the principal findings are nevertheless internationally applicable.

A new mechanistic structural design methodology was presented which has the potential to reduce road construction cost and improve the structural strength of the pavement, primarily by virtue of reduced pavement layer thickness and compaction requirements. The improved functionality of a pavement was addressed by defining the optimum wearing course material selection parameters, based on both road-user acceptability criteria and models of functional defect progression. Where sub-standard wearing course materials are encountered, the functional performance assessment methodology can also be applied in a quantitative assessment framework to assess dust palliative performance in comparison with other dust remediation options. Finally, the concept of maintenance management was addressed in which a maintenance management system model was developed as an aid in identifying the most appropriate haul road maintenance schedule commensurate with minimum total road-user costs. The adoption of the MMS model program for mine haul roads has the potential to generate significant cost benefits when used dynamically, in conjunction with production planning, to optimise mine haul road maintenance activities.

A total haul road design strategy combining mine layout, construction techniques, available material and road maintenance equipment with hauler choice has been developed. Application of these general design and operation optimisation strategies will enable mine operators to realise a significant reduction in haulage and road maintenance costs.

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