Integrated Asset Management Strategies for Unpaved Mine Haul Roads

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Abstract 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 290 tons. Typical axle loads in excess of 200 tons are applied to mine haul road networks that have historically been designed empirically, relying heavily on local experience. Currently, truck haulage costs can account for 10%-50% of the total costs incurred by a surface mine. As the trend in increasing truck size continues, the current pavement systems will prove inadequate. Not only will the maintenance costs of existing roads with inadequate thickness increase, vehicle operating and maintenance costs will also increase prohibitively. There is a need to consider an integrated approach to pavement system structural, functional and maintenance design components, taking into account road construction costs, vehicle operating costs and road maintenance costs. Since mine roads are built and operated by private companies, minimisation of total transportation costs is required. The paper presents an integrated mine haul road asset management strategy and illustrates the value of its application through case studies. Using the asset management strategy, the improvement in structural design resulted in a 29% saving in construction costs and also provided better service, whilst the optimal selection and management of wearing-course materials also provided better functionality at lower total transportation cost. Environmental considerations were addressed by the characterisation of wearing course material performance that enabled a haul road dust management strategy to be developed based on the comparative costs of the suppression solution adopted. Through a case-study application, the benefits of effective dust management and the associated reduction in total construction costs, vehicle operating costs and road maintenance costs is illustrated.

INTRODUCTION

In surface mining operations ultra-heavy trucks hauling payloads in excess of 290 tons apply axle loads in excess of 200 tons to an unpaved mine haul road, albeit at relatively low daily load repetitions. A mine haul road network typically consists of 10-25km of road segments with variable traffic volumes and construction and material qualities. Road networks for these vehicles have historically been designed empirically, relying heavily on local experience. Ever increasing vehicle sizes have resulted in unpredictable road performance and excessive road-user costs. Truck haulage costs can account for up to 50% of the total operating costs incurred by a surface mine. Any savings generated from improved road design and management will benefit the mining company directly as a reduced cost per ton material hauled. However, there is also the need to balance the cost of any asset against its design life. The empirical approach can result in over-expenditure on construction and operating costs, especially in the case of short term roads. Alternatively, it can under-estimate the thickness requirements of longer term roads, leading to premature failure and excessive operating costs. As tonnage increases and larger haul trucks are deployed, not only will the maintenance costs of existing roads of inadequate design increase, vehicle operating and maintenance costs will also increase prohibitively.

The design of mine haul roads encompasses structural, functional and maintenance design aspects. The aim of a structural design is to provide a haul road which can carry the imposed loads over the design life of the road without the need for excessive maintenance. Functional design is centered on the selection and application of wearing course materials. Whilst a strong relationship exists between road structural and functional performance and safe, economically optimal mining operations, the maintenance aspect of haul road design cannot be considered separate from the structural and functional design aspects. Design and construction costs for the majority of haul roads represent only a small proportion of the total operating and maintenance costs. It is possible to construct a mine haul road that requires no maintenance over its service life, but this will be prohibitively expensive. A maintenance-intensive road on the other hand will also be expensive, 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 desired vehicle operating and road maintenance costs.

Wearing course material selection guidelines and a maintenance management system can optimise road performance to minimise total road-user costs. However, considerable time and cost is nevertheless applied to the reduction of haul road dust. All unpaved mine haul roads will generate dust, irrespective of the type of wearing course material used. Optimal wearing course material selection reduces, but does not eliminate the potential to produce dust and water is regularly applied to the road for palliation purposes. Although water-spraying is the most common means of reducing dust, it is not the most efficient means of dust suppression, especially where high evaporation rates and traffic volumes are found in combination with excessive dust. To determine the cost implications of the various dust suppression options available, relative to the cost of improving or rehabilitating the wearing course material, models were developed of dust palliative performance.

Integrated road design and asset management strategies have the potential to generate significant cost savings. For a fleet of Caterpillar 777 (91 ton payload, 161 ton Gross Vehicle Mass (GVM)) rear dump trucks operating on a 7.3km 7% incline, if road rolling resistance is reduced from 8% to 4%, the capital cost of equipment necessary to move 5 million tons per annum is reduced by 29% while the operating costs reduce by 23% *(1)*. For a fleet of 15 trucks of 240 ton payload (376 ton GVM), if operational efficiency can be increased by 10% and fuel consumption (150 litre/hour) reduced by 10% through improved road design and maintenance, this would represent an annual cost saving in excess of R3.5m., or $440 000 (using an exchange rate of R8=1$ and South African costs).

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

With the need therefore to consider the transportation problem holistically, a research project was undertaken in South Africa to develop a design and management system that takes into account the road structural, functional and maintenance design factors. Integrated asset management strategies were developed, encompassing road construction, operation, maintenance and vehicle operating cost components to meet these requirements. Figure 1 illustrates the approach used to integrate the various design components.

Aim and Scope of Paper

The aim of the paper is to present a summary of the structural design system, the pavement deterioration system and the maintenance effectivity as components of an asset management strategy and to demonstrate the value of its application through case studies. Environmental considerations were addressed through characterisation of wearing course material, hauler, climate and traffic volumes, enabling a haul road dust management strategy to be developed. Through a case study application, the benefits of effective dust control as part of the overall asset management strategy are illustrated.

HAUL ROAD STRUCTURAL DESIGN

The structural design of a pavement concerns the ability of the road to carry the imposed loads without the need for excessive maintenance or rehabilitation during the design period. 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.

The CBR method *(2)* has been widely applied to the design of surface mine haul roads in which untreated materials are used. However, when aggregate-surfaced multi-layered mine haul roads are considered in conjunction with stabilised or rock layers, recourse to a mechanistic approach was made to quantify both the extent of any over- or under-design associated with the CBR approach and to determine the optimal multi-layer design *(3)*. The South African Mechanistic Design Method (SA-MDM) is based on a theoretical linear-elastic multi-layer system model of pavement layers. Empirically derived limiting design criteria were 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.

Recommended Mechanistic Structural Design Technique

A number of mine roads were comparatively assessed using the empirical CBR-based and mechanistic-based approaches as described in Thompson and Visser *(4)*. Pavement deflection profiles generated from Multi-depth Deflectometer installations were analysed with the aid of multi-layer linear elastic models to deduce acceptable design criteria in conjunction with a categorisation of the efficacy of the various existing haul road designs. Effective elastic modulus values ascribed to each layer were determined initially by back-calculation and then by recourse to established modulus values and the associated material classification. Several of the pavement designs analysed included rock or stabilised layers at various depths in the structure. When a 240mm thick stabilised layer was located higher in the structure it was observed that the road performed well and was not susceptible to the effects of high axle loads in the upper layers, primarily due to the load carrying capacity of the stabilised layer. This philosophy was incorporated in to the recommended mechanistic structural design of mine haul roads.

The design criterion adopted to assess the structural performance of mine haul roads, namely the vertical elastic compressive strain for each layer below the top layer, correlated well with performance of the road. Those sites exhibiting poor performance and an associated excessive deformation and high maximum deflection were observed to be associated with large vertical compressive strain values in one or more layers. From analysis of the data it was found that various upper limits could be placed on layer vertical strain values, dependent on the predicted life of the road, traffic volumes (as run-of-mine tonnage (ROM)) and required performance index. Figure 2 illustrates the variation in maximum recommended layer vertical compressive strains for a range of traffic volumes, whilst Table 1 summarises a typical application to three categories of haul road in terms of traffic volume, vehicle type and required road performance index.

Mechanistic Design Case Study

For comparative purposes, two design options were considered; a conventional design based on the CBR cover curve design methodology, and the mechanistically designed optimal equivalent, both using identical in-situ and road construction material properties. A Euclid R170 (154 ton payload, 257 ton GVM) truck was used to assess the response of the structure to applied loads generated by a fully laden rear dual wheel axle. The assumption was made of no load-induced elastic deflections below 3 000 mm, based on multi-depth deflectometer measurements on other roads. The various design options are summarised in Figure 3.

In the evaluation of both designs, a mechanistic analysis was performed by assigning target effective elastic modulus values for each layer and a limiting vertical strain of 2000 microstrain. In the case of the CBR-based design, from Figure 3 it is seen that excessive vertical compressive strains were generated in the top of layers 2 and 3. For the optimal mechanistic structural design, no excessive vertical compressive strains were generated in the structure, primarily due to the support generated by the shallow rock layer. Surface deflections were approximately 2mm compared with 3,65mm for the CBR-based design which, whilst not excessive, when accompanied by severe load induced strains, would eventually initiate premature structural failure. The proposed optimal design thus provided a better structural response to the applied loads than the thicker CBR based design and, in addition, did not contradict any of the proposed design criteria.

TABLE 1 Summary of Haul Road Categories

Haul Road Category	Max daily traffic volume (kton)	Traffic type (largest allowable vehicle) GVM ton	Required performance index[1]	Description
Category I	25	480	9	Permanent high volume main coal hauling roads from ramps to ROM tip. Operating life at least 20 years.
Category II	14	480	6	Semi-permanent overburden high- or low-wall ramps, in-pit coal and overburden hauling roads on blasted overburden, medium traffic volumes. Operating life under 10 years.
Category III	7	386	4	Transient overburden in-pit ramps, low traffic volumes Operating life under 3 years.

1 Based on acceptable structural performance of roads and maximum deflection under fully laden rear wheel, where 10=excellent performance, 1=unacceptably poor performance, following Thompson and Visser (4)

A construction cost comparison compiled from contractor tender unit costs revealed that a 29% variable cost saving could be realised when the optimal mechanistic design is adopted, compared with the CBR design, by virtue of the reduced material volumetric and compaction requirements. In terms of total construction cost (including preliminary and general costs) a 17% total cost saving was realised. Subsequent to this analysis at least 10 roads were constructed following the mechanistic design method and during the extremely wet summers of 1996 and 2000, superior performance was reported, compared with the previously existing roads.

HAUL ROAD DETERIORATION SYSTEM

The functional performance of a mine haul road is primarily reflected by the ability of a haul road to provide an economic, safe and vehicle friendly ride. This is dictated to a large degree through the choice, application and maintenance (blading) of wearing course materials in combination with a structural design of adequate capacity. Current functional performance assessment methods were found to be subjective and localised in nature and any deterioration in pavement condition consequently hard to assess *(5)*. Poor functional performance is manifest as poor ride quality, excessive dust, increased tyre wear and damage and an accompanying loss of productivity. This results in increased overall vehicle operating and maintenance costs.

The experimental approach used to determining suitable material selection guidelines involved the analysis and quantification of a range of factors which determined how well the various wearing course material types met road-user requirements. In general, these factors are the material type itself, together with road geometry, 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 *(6)*.

Recommended Wearing Course Material Selection Guidelines

The development of wearing course material selection guidelines was based on the experimental analysis of road deterioration, supplemented with road-user assessments of haul road functional defects and their impact on trafficability, safety and road-user cost.

The TRH20:1991 *(7)* wearing course material selection guidelines were found to be a suitable source for the specification of mine haul road wearing course material parameter requirements. A revised selection parameter range was derived as shown in Figure 4. The selection range (1-2) was based on road-user preference for much reduced wet slipperiness, dustiness and dry skid resistance defects. The specification was based on shrinkage product (S_p) and grading coefficient (G_c) limits of 85-200 and 20-35 respectively. In addition, from an analysis of material property parameters and their association with the functional defects analysed, parameter ranges were additionally specified for density, dust ratio, Atterberg limits, CBR and maximum particle size *(8)*.

By analysing road defect and wearing course material trends, the predictive capability of the specification was enhanced by showing the variation in functional defects which would arise when departures are made from recommended parameter limits. By incorporating material property values into deterioration progression models, mine operators can determine the practical implications of using a sub-standard wearing course material or blends of materials. Sub-standard materials will impact on overall haul road functionality, individual defect scores and road-user acceptability, as well as road maintenance frequency. Segments of the haul road network can therefore be designed from a functional perspective to provide similar overall functional performance, albeit with different traffic volumes and material types. This is particularly important in situations where a shortage of suitable wearing course materials exist and priority must be given to high traffic volume – maintenance intensive roads.

Haul Road Wearing Course Material Selection Case Study

Figure 4 illustrates the location of a wearing course material (M1) in terms of the proposed selection guidelines, together with two other materials that could be used for blending with the current wearing course (BS and ASH). The wearing course material (M1) is seen to be dusty when dry and liable to skid resistance hazards when wet (typically a slippery surface after rain or watering).

If the wearing course material deterioration is analysed (Thompson and Visser *(5)*), the high defect score and rate of deterioration at low (5kton/day) and high (45kton/day) traffic volumes, as shown in Figure 5, typifies the unsuitability of the material.

In order to improve the functional performance of the wearing course, some blending of materials was necessary. Using the recommended material specifications, in conjunction with the defect score progression model it was possible to determine the optimal mix of materials to rehabilitate the road. In this case, 40% BS and 30% ASH was added to the original wearing course to achieve a mix within the specified selection range. Figure 5 shows the much reduced predicted deterioration rate for the new wearing course when subjected to the same traffic volumes. The mine previously bladed both high- and low-volume roads when the functional defect score exceeded 60, i.e. at 3½-day intervals. Using the same functional defect score, following rehabilitation of the road and the associated lower deterioration rate, the blading interval was increased to 7- and 10-days respectively, resulting in road maintenance cost savings.

The case study addresses individual functional defects and their reduction through optimal material selection and reduced deterioration rates. If total haulage costs are considered, comprising vehicle operation (fuel, tyres, maintenance parts and labour) and maintaining the road (grader and water-car operating costs), the optimal frequency of wearing course maintenance commensurate with minimum vehicle operating and road maintenance costs can be determined.

HAUL ROAD MAINTENANCE SCHEDULING AND MANAGEMENT

Poor haul road maintenance management results in excessive expenditure on vehicle operating costs or road maintenance equipment operation. However, whilst mine operators agreed that road maintenance was critical to efficient hauling operations, there was no structured approach in evaluating alternative maintenance intervals nor the effect on total road-user costs.

By developing a maintenance management system (MMS) for mine haul roads, the optimum maintenance frequency for each road segment of a mine haul road network was determined, based on lowest total vehicle operating and road maintenance costs for the network. Where equipment availability limits the amount of maintenance time available, priorities can be assigned based on traffic volume - wearing course deterioration characteristics.

The MMS was developed from consideration of road maintenance and vehicle operating costs associated with existing wearing courses and evaluated against those estimated from models. Two elements formed the basis of the economic evaluation, namely pavement roughness progression and vehicle operating and road maintenance costs.

Road roughness progression forms the basis of the MMS since roughness, which affects rolling resistance, is the principal measure of pavement condition that can be directly related to both vehicle operating costs and the frequency of maintenance activities. Using the experimental procedure outlined by Thompson *(6)*, a model for roughness progression was developed in which wearing course material parameters, traffic volumes and maintenance interval were significant variables.

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. Whilst the vehicle operating cost models for fuel and tyres could be determined from truck and tyre manufacturers data combined with mine records, vehicle maintenance cost and labour components were poorly defined and thus existing models developed for public commercial trucks were used. Although the parameter ranges were dissimilar 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. The model was compared with available mine data 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. These models are discussed in more detail by Thompson and Visser *(5)*.

The interaction and influences of the various models proposed to represent vehicle operating costs, road maintenance costs and the progression of road roughness was analysed using a systems approach as shown in Figure 6. The evaluation of 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 available maintenance equipment.

When analysing the results of individual mine simulations, the actual mine operating practice was seen to closely resemble that predicted by the model, especially with regard to increased maintenance intervals on lightly trafficked roads. A typical result is illustrated in Figure 7 from which it is seen how total vehicle operating costs are minimised at the optimal individual segment maintenance frequency interval. From an analysis of the rate of change in vehicle operating and road maintenance costs for individual segments of the mine road network with changes in maintenance frequency, an annual over-expenditure of R310 000 ($38 800) or 4% of total road-user costs was associated with the sub-optimal maintenance strategies previously practiced. Since the model can accommodate various combinations of traffic volumes and road segments, when used dynamically in conjunction with production planning, it has the potential to generate significant cost benefits.

HAUL ROAD DUST MANAGEMENT STRATEGY

Wearing course material selection guidelines used with a MMS will optimise road performance at the desired total road-user costs. However, considerable time and expenditure is nevertheless applied to the reduction of the haul road dust defect. Dust generation from mine roads has been recognised as both a health and safety issue *(9, 10)* and mines regularly apply a water-spray to the road to allay dust. Water-spray based dust suppression is the most common means of reducing dustiness on mine haul roads. The combination of a water-car and regular spray applications of water provide a relatively inexpensive, but not necessarily efficient, means of dust suppression. To determine the cost and management implications of dust suppression on mine haul roads using water or other chemical palliatives, a study was undertaken at 10 mine sites in southern Africa from which a dust palliative management strategy was developed *(11)*.

An evaluation of water spraying as a means of dust palliation was initially investigated and a model developed to predict the re-application frequency of water to maintain a specified degree of dust palliation. A Hund Tyndalometer was used to obtain a simple two-dimensional profile for dust generation per vehicle pass, based on peak dustiness (mg/m^3 minus 10ìm dust) and plume duration. Analysis of the data enabled a first estimate to be made of the time taken for the degree of palliation to reach zero and the effect of climate, specifically evaporation rates, on this time.

The management strategy for water-spray dust suppression was based on user defined levels of dust defect acceptability, both from a health and safety point of view, as given in Table 2 . Mine personnel's opinion was used to attach defect scores to specific dust readings during the monitoring process. In general, the consensus was that a dust defect score of 2 would represent an ideal dust defect intervention level. This defect score was based primarily upon the visual effects (road safety and driver discomfort), rather than any perceived health impact.

TABLE 2 Classification of the Degree of Haul Road Dust Defect

Dust Defect Degree Descriptions and Associated Peak Dust Levels (approx. mg/m^3 x100 for -10ìm dust)				
Degree 1 <350	Degree 2 351 to 2350	Degree 3 2351 to 4500	Degree 4 4501 to 5750	Degree 5 >5751
Minimal dustiness	Dust just visible behind vehicle.	Dust visible, no oncoming vehicle driver discomfort, good visibility.	Notable amount of dust, windows closed in oncoming vehicle, visibility just acceptable, overtaking difficult.	Significant amount of dust, window closed in oncoming vehicle, visibility poor and hazardous, overtaking not possible.

An approximate appreciation of the role of climatic condition, expressed as mean monthly evaporation rates, on the time taken for the degree of dust palliation to reduce to zero using water-spray suppression was determined from a number of tests in various climatic regions (following Weinert*, 12*). To determine the re-application interval and therefore eventually model the cost-effectiveness of water-spray suppression compared with other strategies, the effect of traffic speed on peak and total dustiness of various types of wearing course materials was modelled.

An estimate of the dustiness associated with a particular wearing course material was found from seven test sites where data was recorded and analysed to model three parameters; the mass of dust as loose material on the road (significant model parameters were wearing course 0,425mm and 0,075mm fractions, shrinkage product and the loose material 0,425mm fraction), the total dustiness (from consideration of peak and period of plume and truck size and type) and the total dustiness (a function of vehicle speed, size and wind shear, traffic volume and mass of loose material on the road). By combining each of these models with the maximum allowable dust defect score and the associated peak value, the degree of palliation required to maintain this maximum defect score, and the associated re-application time, was determined. When combined with models for total dust generation and the effect of climate on generation rates, a first estimate of re-application frequencies could be made. Full details of the approach are presented by Thompson and Visser *(11)*.

An assessment of a number of chemical palliative products was undertaken with which to benchmark their performance and identify appropriate management strategies. Products analysed include hygroscopic salts, lignosulphonates, petroleum resins, polymer emulsions and tar and bitumen products. Although the experimental design required each product to be tested with various combinations of wearing course material types and traffic volumes, mine site restrictions limited the range of values analysed. Nevertheless, a more realistic estimate could be made of the degree of palliation achieved and the palliative degeneration rates (based on 50-154 truck repetitions per day on ferricrete, coal discard or mixtures of wearing course materials), than the often optimistic performance estimates of product suppliers. The palliative performance data generated was then used in the model developed for palliative evaluation and management.

The development and evaluation of dust management strategies required an analysis of the relative costs of alternative palliation options, such that the most cost-efficient option can be determined, together with an indication of the sensitivity of the selection in terms of the primary modeling parameters. A pre-requisite of any cost evaluation is a model that provides a rapid means of making a consistent comparison of the real costs of alternative control measures. Changes in cost of dust control and the reduction in emissions resulting from the introduction of alternative strategies are utilised to evaluate dust control management options. This allows the economic implications of the introduction of alternative strategies to be expressed in terms of a base-case cost, in this case water-based spraying.

The development of the model consisted of identification of the key components that affect the overall cost of dust control and their interrelationship and effect on the total cost (R/m^2 palliated road). The major cost elements for dust control included capital equipment, operation and maintenance costs, together with material cost (palliative cost) and activity-related costs such as surface preparation, dust palliative application, grading and watering and finishing, for either a mix-in or spray-on establishment or re-application. Other cost elements include equipment downtime and vehicle maintenance costs. These parameters were, in turn, influenced by the selected palliative application methodology and frequency. Costs associated with reduced road maintenance intervals are also important since improvements in functionality were seen to be a major benefit of dust palliatives, especially where re-application interval could be made to coincide with scheduled road maintenance activities determined from a MMS assessment.

The primary data classes analysed in the model incorporated the following;

1. Water-based spray re-application model (l/m^2 applied and frequency)
2. Road and climate data specific to area being assessed (for water-based spraying model only)
3. Water-car operating cost data (for water-based spraying)
4. Water and chemical palliative application rate and cost data
5. Equipment activity productivity and cost data for establishment, application (spray-on or mix-in and spray-on re-application).
6. Road functionality data and required maintenance intervals

Figure 8 illustrates application of the model to the previous wearing course material case study, where a maximum dust defect score of 2 is applied (typically a heavily trafficked Category I type road with the potential for numerous vehicle interactions). The cost effectiveness of the various dust management strategies for either water-spraying, the application of a chemical palliative (in this case a polymer-emulsion product which requires re-establishment every 3 years), or improvement of the wearing course material, is illustrated. If no improvement to the wearing course material can be made, then application of the polymer-emulsion palliative will render the lowest overall treatment cost. When the wearing course material is improved, the benefits are evident in terms of the much reduced cost of water-spraying. Over the short term (2 years), water-based spraying will offer the cheapest means of suppression (primarily as a result of the relatively expensive mix-in establishment required with the polymer-emulsion). For longer-term applications, the polymer-emulsion option is marginally cheaper and may offer other unquantified benefits such as improved wet weather trafficability, reduced erosion and dry skid resistance.

CONCLUSIONS

The use of ultra-heavy haul trucks for the transport of material on surface mines, in conjunction with empirical mine haul road design techniques, have been shown to be inadequate. There was a need for improved technologies encompassing the construction and management techniques of mine haul roads, appropriate for the wheel loads of vehicles now. By combining the research results from a study of structural, functional and maintenance design, together with models derived for haul road dust management strategy evaluation, an integrated asset management strategy for a network of mine haul roads was developed. Whilst the research was based on southern African road construction materials and climatic conditions, the principal findings are nevertheless internationally applicable.

A mechanistic structural design methodology was presented which facilitates the use of pavement layer vertical strain criteria in conjunction with required performance and traffic volumes to determine the most appropriate layer thickness, thereby reducing road construction cost and improving the structural strength of the pavement. 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. The selection methodology, in conjunction with deterioration system models, enables operators to schedule road blading dynamically, according to traffic volumes and wearing course material type, for optimum functionality. By combining the functional deterioration models with those of road-user and vehicle operating costs, 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.

A model for the evaluation of dust management strategies was also developed, based on the combined effects of traffic type, speed and volumes on wearing course material dust generation rates and palliative system efficiencies and cost. Application of the model enables operators to identify where on the road network dust is problematic and to identify the most appropriate palliation option and its cost.

A total haul road asset management strategy combining mine layout, construction techniques, available material and road maintenance equipment choice has been developed. It has been shown how, through the application of these design and asset management strategies, mine operators can realise significant reductions in haulage and road maintenance costs whilst achieving optimal asset utilisation.

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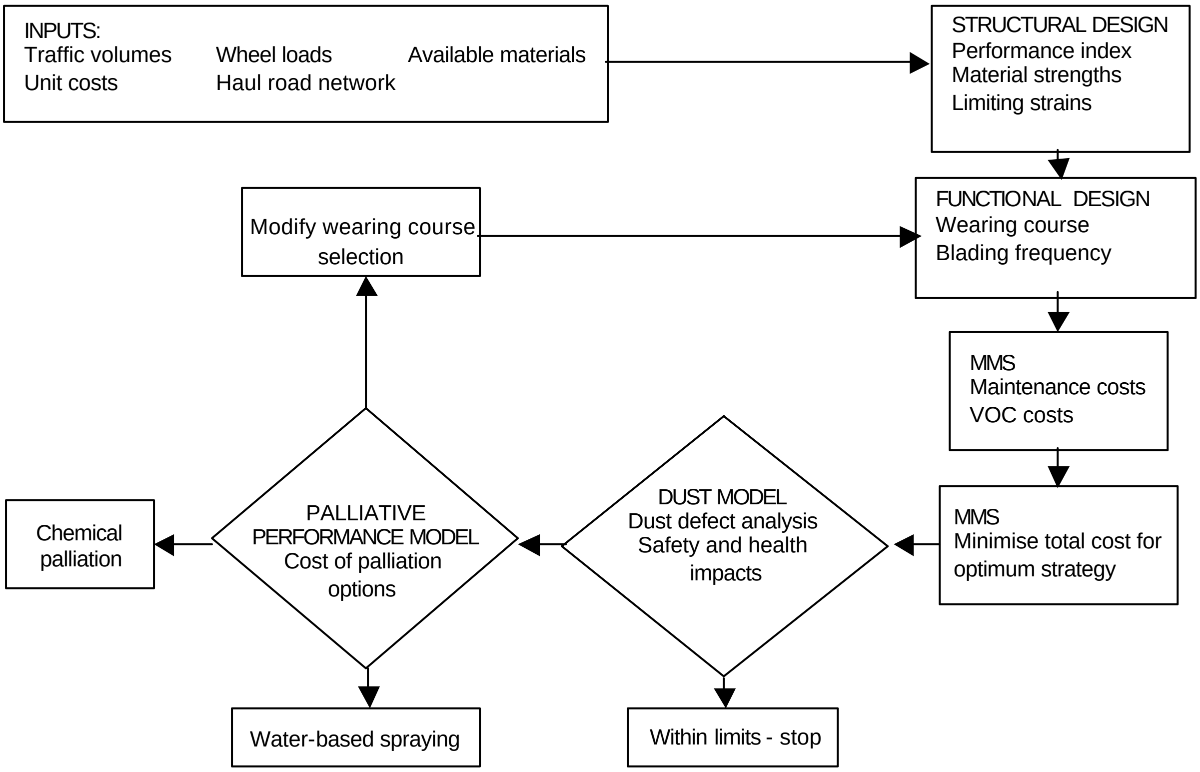


FIGURE 1 **Integrated haul road management system.**

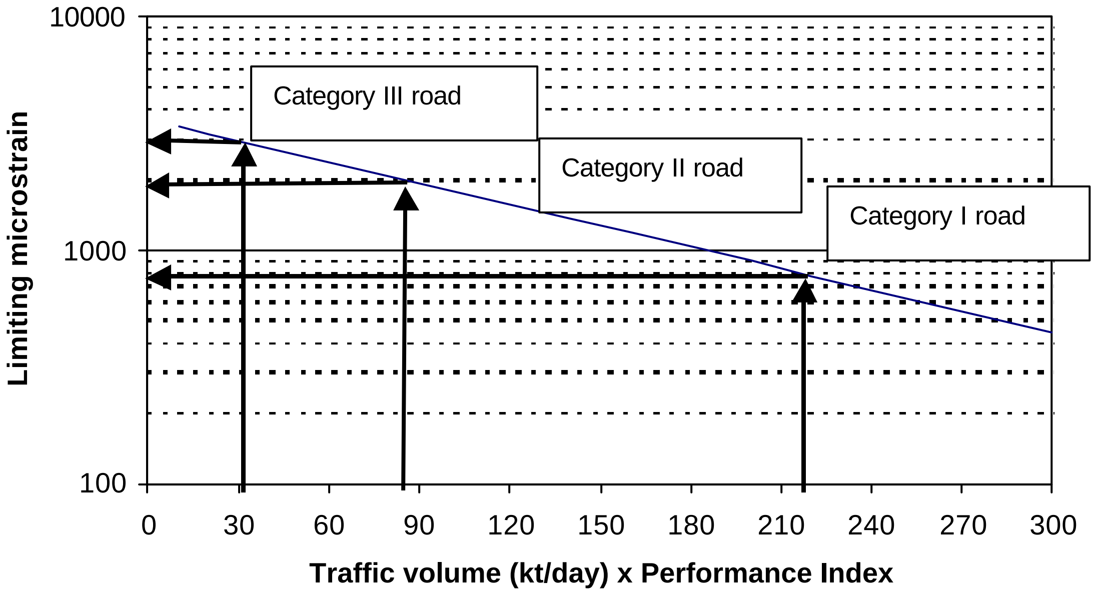


FIGURE 2 **Pavement layer vertical compressive strain limits for typical Category I-III haul road structural design.**

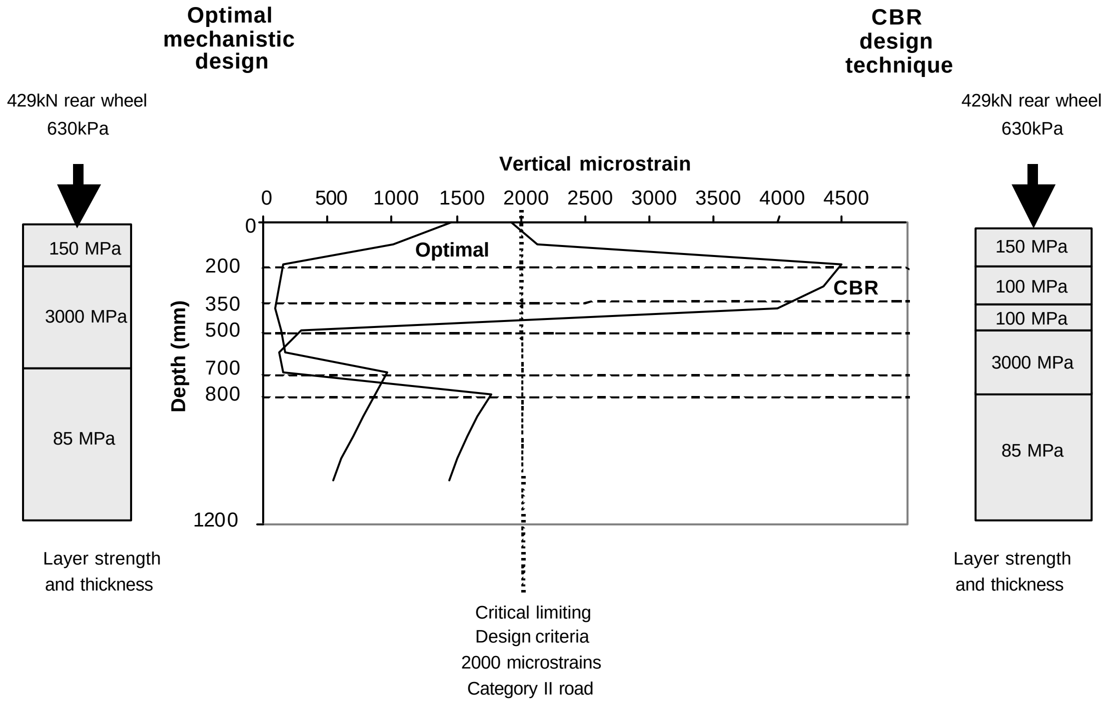
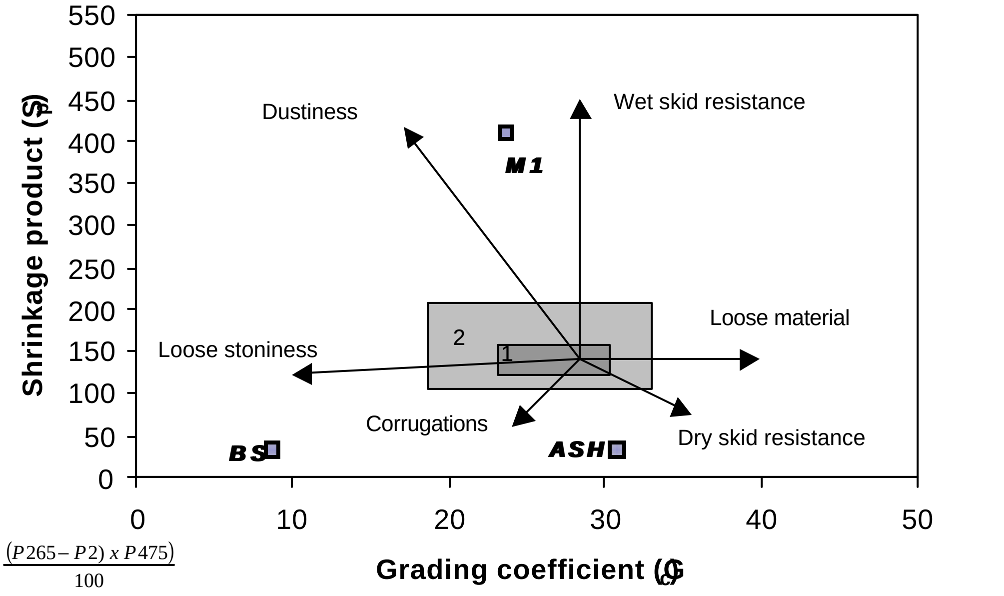


FIGURE 3 Results of comparison in terms of vertical strain design criteria for CBR- and mechanistic-based structural designs.



$$G_c = \frac{(P265 - P2)\ x\ P475)}{100}$$

$Sp = Linear\ shrinkage\ x\ P425$

P265, P2, P472, P425 Percent passing sieve size in mm

FIGURE 4 Recommended wearing course material selection ranges 1-2.

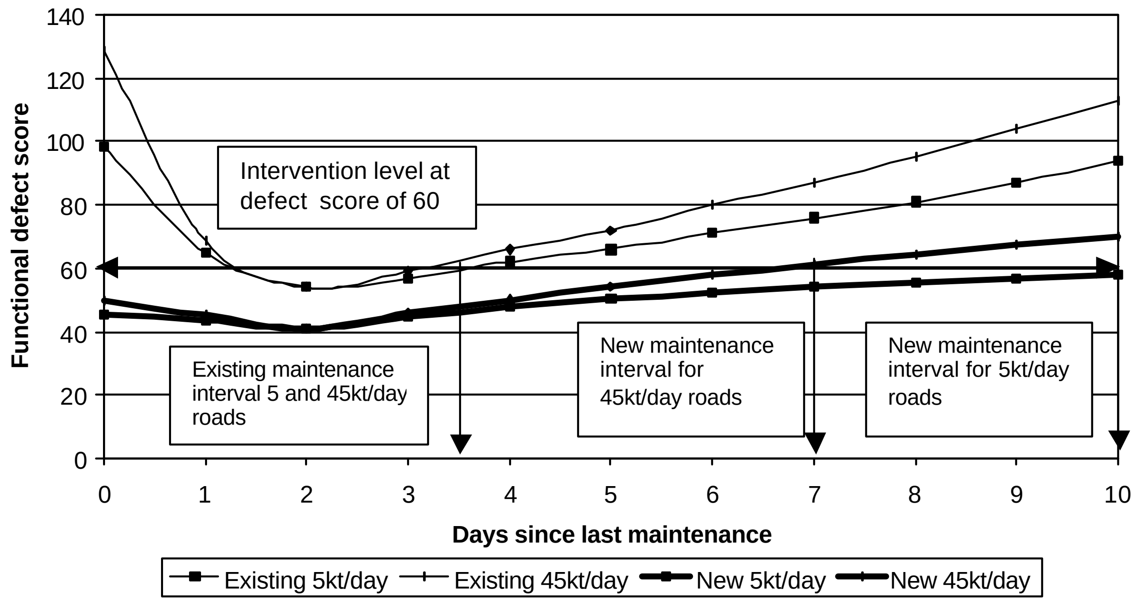


FIGURE 5 Predicted improvement in functionality for new wearing course material mix at 5 and 45kt/day traffic volumes.

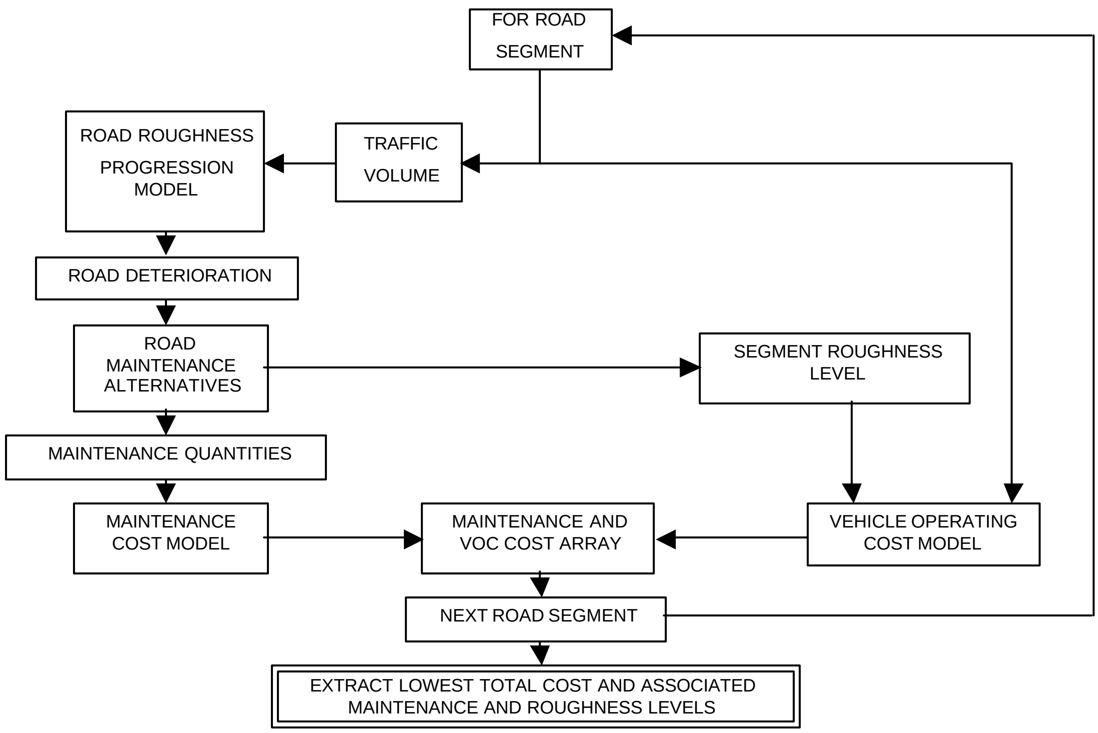


FIGURE 6 Flow diagram of MMS for mine haul roads (for a single maintenance strategy iteration).

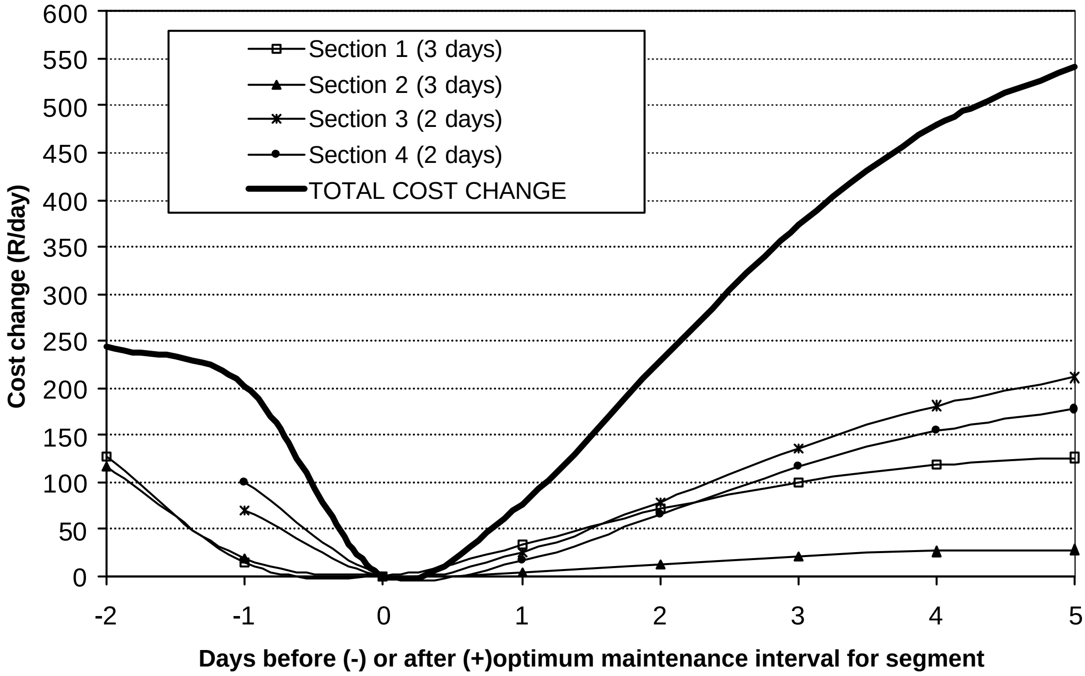


FIGURE 7 Haul road segment and total road-user cost variation with maintenance interval.

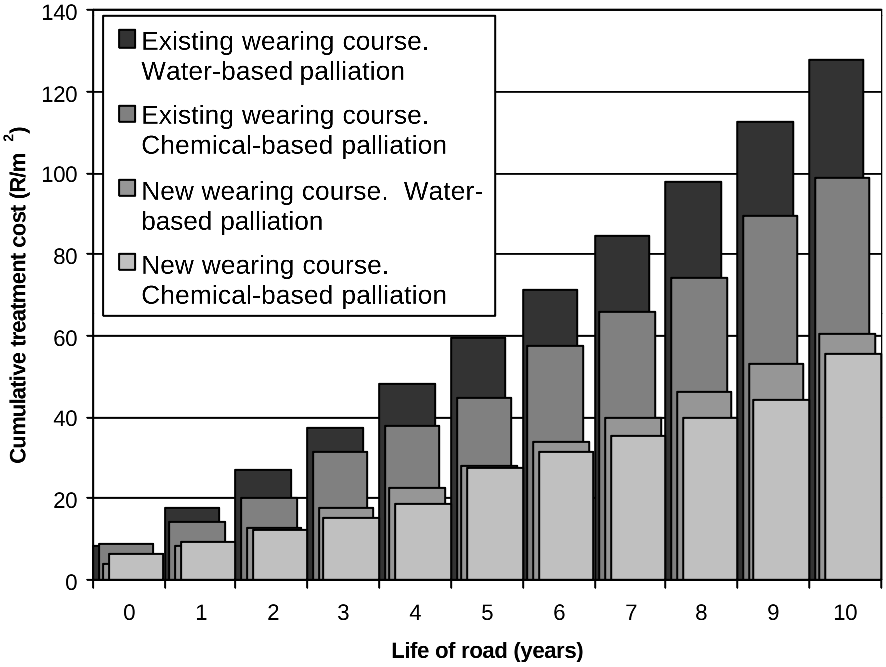


FIGURE 8 Dust management costs for existing or improved wearing course materials in conjunction with water- or chemical-based palliation.