



## Ultra-heavy Axle Loads: Design and Management Strategies for Mine Pavements

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### Abstract

The drive for greater cost efficiencies in surface mining has led to the development of ultra-heavy off highway trucks currently capable of hauling payloads of 345 tons. Typical axle loads in excess of 400 tons are applied to unpaved mine haul roads that have historically been designed empirically, relying heavily on local experience. In the absence of a formal haul road design methodology, good roads eventually result – but the learning curve is steep & slow. This approach does not lend itself to an understanding of the road design process and more importantly, if the haul road performance is sub-standard, does not easily allow the underlying cause of the poor performance to be identified. With the trend in increasing truck size, haul road performance has become unpredictable, difficult to manage and costs of both maintaining the road and operating the truck have also increased prohibitively. Most surface mine operators agree good roads are desirable, but find it difficult to translate this requirement into an effective and responsive road design and maintenance management system.

To meet this need, an integrated approach to pavement system geometric, structural, functional and maintenance design components was developed, 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. This paper presents an integrated mine haul road design and management strategy and illustrates the value of its application through several application case studies. A mechanistic approach to 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, both from a rolling resistance and fuel consumption perspective and a fugitive dust emission modelling and palliation perspective.

### 1 Introduction

In truck-based hauling systems, the mine haul road network is a critical and vital component of the production process. As such, under-performance of a haul road will impact immediately on mine productivity and costs. Operations safety, productivity and equipment longevity are all dependent on well-designed, constructed and maintained haul roads. The mine haul road is an asset and should, in conjunction with the haul trucks using the road, be optimally designed and its routine maintenance managed accordingly. An ad-hoc or empirical approach to haul road design is generally unsatisfactory because it has the potential for over-expenditure, both on construction and operating costs, arising due to;

- The over-design and specification of short term low-traffic volume roads
- The under-design, leading to excessive operating and road maintenance costs and premature failure in the case of longer-term higher-volume roads.

Economy of scale and the increase in haul truck payload has so far seen the ultra-class truck (220t and larger) population rise to over 40% of all mine trucks used (Gilewicz 2006). With

this increasing size, haul road performance can be compromised, resulting excessive total road-user costs; often seen directly as an increase in cost per ton hauled, but also indirectly as a reduction production rates and vehicle and component service life. Truck haulage costs can account for up to 50% of the total operating costs incurred by a surface mine and any savings generated from improved road design and management benefit the mining company directly as a reduced cost per tonne of material hauled.

Central to the cost of truck hauling is the concept of rolling resistance (expressed here as a percentage of Gross Vehicle Mass (GVM)). It is a measure of the extra resistance to motion that a haul truck experiences and is influenced by tire flexing and internal friction and most importantly, wheel load and road conditions. Road surface deflection or flexing also generates resistance, with the truck tire running “up-grade” as the deflection wave pushes ahead of the vehicle. Taking an electric-drive rear-dump ultra-truck of 376t (GVM) as an example, on a ramp road with a basic rolling resistance of 2%, an additional 1% rolling resistance will reduce truck speed by 10-13%, whilst on a flat surface road, the truck speed will reduce by between 18-26%.

Whilst many concepts from highway engineering can be adapted to the design, construction and management of mine roads, significant differences in applied loads, traffic volumes, construction material quality and availability, together with design life and road-user cost considerations, the requirement for a tailored design solution is readily apparent.

## **1.1 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 maintenance management 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 selection and management strategy to be developed. Through a case-study application, the benefits of these improved design guidelines are illustrated.

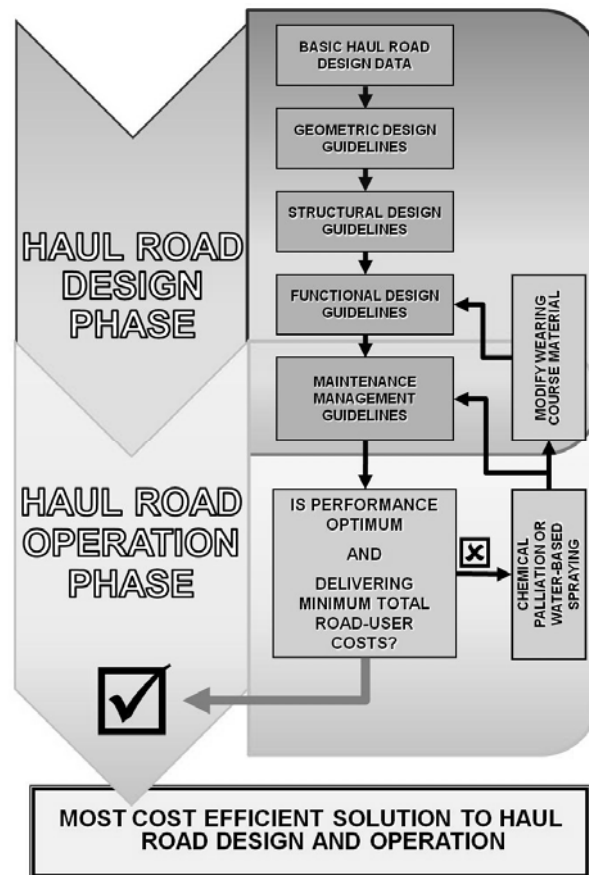
## **2 Components of an integrated mine haul road design**

The operating performance of a mine road can be subdivided into four distinct design components and when designing and constructing a haul road for optimal performance, these design components are best addressed using an integrated approach. If one design component is deficient, the other components may not work to their maximum potential and road performance is often compromised. This will most often be seen as ‘maintenance intensive’ or high rolling resistance roads, translating to increased equipment operating, downtime and repair costs. The cure, however, is not necessarily just ‘more frequent maintenance’; no amount of maintenance will fix a poorly-designed road.

Design and management of haul road systems should also be approached holistically, especially with regard to the benefits achieved from various solutions to enhance productivity. Whilst, for instance, trolley-assist may improve cycle times and reduce cost per tonne hauled, it is first necessary to evaluate the extent to which an existing haul road network meets optimal design requirements before resorting to solutions that do not directly address the key deficiencies of the existing road system. The recommended approach is therefore to assess the extent to which the asset (the current road network) exhibits scope for improvement and, once optimized, then revert to resource supplementation to leverage these benefits through optimal asset and resource interaction.

Figure 1 illustrates such an integrated approach, based on the geometric, structural (layerworks), functional (wearing course) and maintenance management components,

together with an evaluation methodology for the selection and application of dust palliatives. These design components form the basis of the following section discussions.



**Figure 1** Integrated haul road design and management system components (after Thompson, 2008)

The first component, that of geometric design, is commonly the starting point for any haul road design and refers to the layout and alignment of the road, in both the horizontal and vertical plane. The ultimate aim; to produce an optimally efficient and safe geometric design, can only be achieved when sound geometric design principles are applied in conjunction with the optimal structural, functional and maintenance designs.

The aim of a structural design is to provide a haul road that can carry the imposed loads over the design life of the road without the need for excessive maintenance. It is focused on the design of road layerworks and the response of construction materials in and under the road to the truck wheel loads.

The functional design is centered on the selection of wearing course (or surfacing) materials; the most suitable choice, application technique and maintenance strategy is required. Commonly, the running surface of a mine road is a gravel mix, which lends itself to maintenance (blading, or, over the longer term, rehabilitation). To improve performance of the material, palliation and/or stabilization is often considered, primarily to reduce both dust generation and material degeneration, the latter leading to increased rolling resistance and associated road maintenance.

The maintenance aspect of haul road design cannot be considered separate from the geometric, structural and functional design aspects since they 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 vehicle operating and road and vehicle maintenance costs. The use of an appropriate road maintenance management strategy will generate significant cost savings by virtue of a better understanding of the relationship between wearing course material degeneration rates (manifest as increasing rolling resistance on the road) and its influence on both cost per tonne hauled and the cost of road maintenance itself.

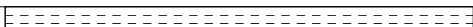
A mine road network often comprises various roads, each with a specific function, traffic type (size of truck), traffic volume, service level (performance) and operating life. A road classification system should be developed, according to these parameters as part of a mine-wide common framework for road design. This can be used as the starting point for design guidelines for construction personnel, to enable them to easily determine what design guideline is appropriate when constructing new, or evaluating and rehabilitating existing mine roads. Clearly, not all roads are 'equal' and thus the approach to design and management must be tailored to apply more resources to high volume, long-term and high cost-impact road segments across the network. Figure 2 illustrates typical haul road design categories, the accompanying data forms the basic input to the four 4 design categories previously discussed.

### 3 Geometric design

The geometric layout of a mine haul road is dictated to a great extent by the mining method used and the geometry of both the mining area and the orebody. Mine planning software enables various haul road geometric options to be considered and the optimal layout selected, both from a road design and economic (lowest cost of provision) perspective. Whilst these techniques often have default design values embedded in the software, it is nevertheless necessary to review the basic concepts of geometric design if any modifications are to be considered in the design of mine roads, either on the basis of economics or, more critically, from a safety perspective.

The road layout – or alignment, both horizontally and vertically is generally the starting point of the geometric design. Practically, it is often necessary to compromise between an ideal layout and what mining geometry and economics will allow. Any departure from the ideal specifications will result in reductions of both road and transport equipment performance. Broadly speaking, safety and good engineering practice require haul road alignment to be designed to suit all vehicle types using the road, operating within the safe performance envelope of the vehicle, or, where this is not possible, at the speed limit applied. Ideally, geometric layout should allow the vehicles to operate at their maximum safe speed, but since the same road is used for laden and unladen haulage, there is often the need to minimize laden travel times, through appropriate geometric alignment, whilst accepting compromise (generally in the form of speed limits) on the unladen return haul. Since considerable data already exists pertaining good engineering practice in geometric design (Kaufman and Ault, 1977; USBM, 1981; Thompson and Visser, 1999, Tannant and Regensburg 2000), readers are referred to these publications for more detail.

**Table1.** Example classification system for a particular mine haul road network

Haul Road Category	Typical Description	Range of maximum permissible vertical elastic strains ( $\mu$ strains)	Limiting pavement layer vertical compressive strain values for mine haul road structural design
			10000 

		Traffic volumes > 100kt/day	Traffic volumes < 100kt/day	
CATEGORY I	Permanent life-of-mine high traffic volume main hauling roads and ramps in- and ex-pit. Operating life >20 years	900	1500	
CATEGORY II	Semi-permanent medium- to high traffic volume ramp roads in- and ex-pit. Operating life >10 years	1500	2000	
CATEGORY III	Shorter-term medium- to low-volume in-pit bench access, ex-pit dump, or ramp roads. Operating life <5 years (@ > 50kt/day) or <10 years (@ <50kt/day)	2000	2500	Maximum permissible vertical strains can also be determined from ( <i>kt/day</i> x <i>performance index</i> ) where performance index is defined as; 1 Adequate but fairly maintenance intensive 2 Good with normal maintenance interventions 3 Outstanding with low maintenance requirements

## 4 Haul road structural design

The CBR method (Kaufman and Ault, 1977) has been widely applied to the design of mine haul roads in which untreated materials are used. However, when multi-layered roads are considered in conjunction with a base layer of selected blasted waste rock, a mechanistic approach is more appropriate. When a selected waste rock layer is located under the wearing course, road performance is significantly improved, primarily due to the load carrying capacity of the waste rock layer which reduces the susceptibility of the soft sub-grade and in-situ to the effects of high axle loads. It also has the added advantage of reduced construction costs (by virtue of reduced volumetric and compaction requirements), compared with the CBR cover-curve design approach (Morgan et al, 1994; Thompson and Visser 1996).

The South African Mechanistic Design Method (SARB, 1994) 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.

### 4.1 Recommended Mechanistic Structural Design Technique

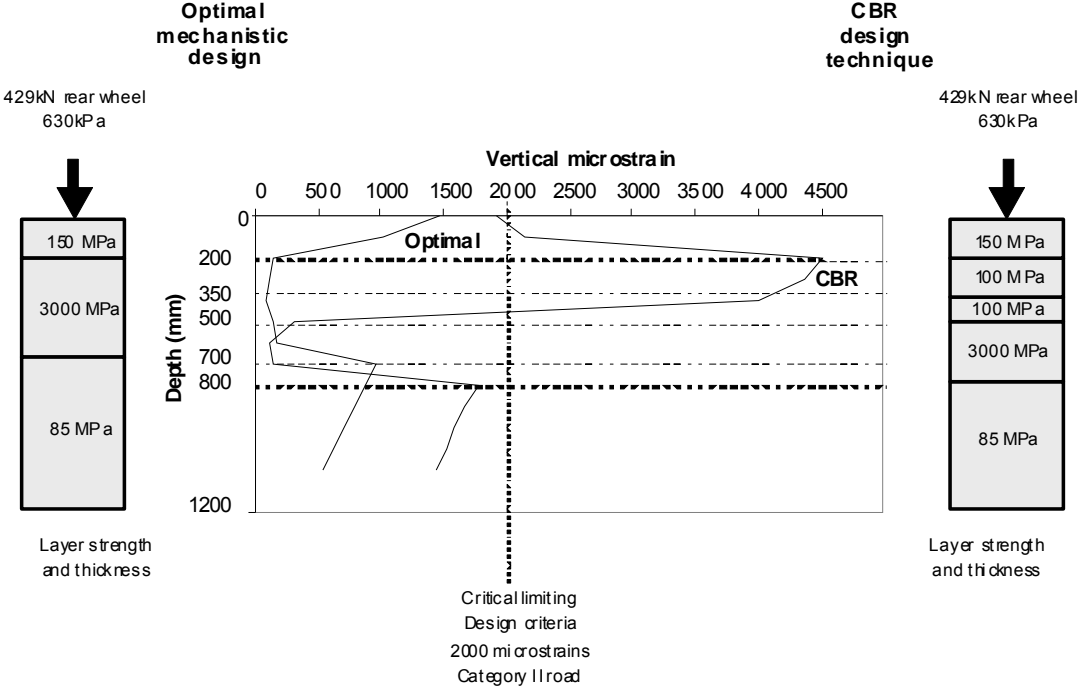
A number of mine roads were comparatively assessed using the empirical CBR-based and mechanistic-based approaches as described by Thompson and Visser (1996). Pavement deflection profiles generated from Multi-depth Deflectometer installations were analysed with the aid of multi-layer linear elastic models 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 latterly 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 seen 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 a high maximum deflection were seen to be associated with large vertical compressive strain values in one or more layers. From analysis of the data it was found that various upper limits could be placed on layer vertical strain values, dependent on the envisaged life of the road, traffic volumes and required performance index, as illustrated in Figure 1.

### 4.2 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 Hitachi EH3000 (156t payload, 278t GVM) rear dump truck was used to assess the response of the structure to applied loads generated by a fully laden rear dual wheel axle and the assumption, based on multi-depth deflectometer measurements on other roads, was made of no load-induced elastic deflections below 3 000 mm. The various design options are summarised in Figure 2.



**Figure 2.** Results of comparison in terms of vertical strain design criteria for CBR- and mechanistic-based structural designs.

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 2 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 contravene any of the proposed design criteria.

A 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 locally extremely wet summers of 1996, 2000 and 2006, superior performance was reported, compared with the previously existing roads.

## 5 Haul road deterioration and functional design

Equally important as the structural strength of the design, is the functional trafficability of the haul road. This is dictated to a large degree through the selection, application and maintenance of the wearing course (or road surfacing) materials. Poor functional performance is manifest as poor ride quality, excessive dust, increased tire 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 functional design of a haul road is the process of selecting the most appropriate wearing course material or mix of materials, typically natural gravel or crushed stone and gravel mixtures that are commensurate with safety, operational, environmental and economic considerations. The most common wearing course material for haul roads remains compacted gravel or gravel and crushed stone mixtures. In addition to their low rolling resistance and high coefficient of adhesion, their greatest advantage over other wearing course materials is that roadway surfaces can be constructed rapidly and at relatively low cost. As with structural designs, if local mine material can be used for construction, the costs are all the more favourable. This cost advantage is, however, not apparent in the long term if the characteristics of the wearing course material result in sub-optimal functional performance.

An ideal wearing course should minimise critical unpaved (gravel) mine haul road defects such as skid resistance – wet, & dry, dustiness, loose material, corrugations, stoniness – loose & fixed, potholes, rutting and cracking (slip, longitudinal and crocodile), (Thompson and Visser, 2006).

By examining which wearing course material property parameters lead to these defects, a specification has been developed for wearing course materials selection. The specifications are based on an assessment of wearing course material shrinkage product ( $Sp$ ) and grading coefficient ( $Gc$ ), defined in Equations 1 and 2.

$$Sp = LS \times P425 \quad \text{(Equation 1)}$$

$$Gc = \frac{(P265 - P2) \times P475}{100} \quad \text{(Equation 2)}$$

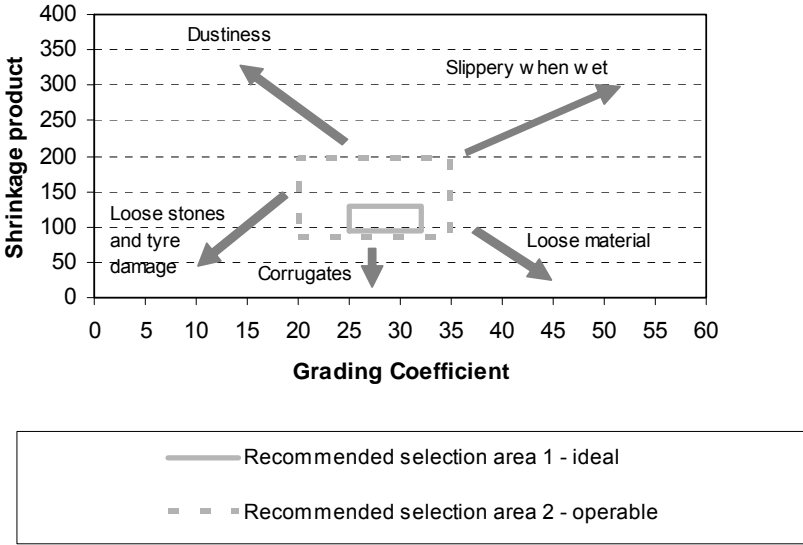
where;

$LS$	=	Bar linear shrinkage
$P425$	=	Percent wearing course sample passing 0.425mm sieve
$P265$	=	Percent wearing course sample passing 26.5mm sieve
$P2$	=	Percent wearing course sample passing 2mm sieve
$P475$	=	Percent wearing course sample passing 4.75mm sieve

A suitable wearing course material can be determined from the selection chart (Figure 3), in terms of the above two parameters. If the three most critical haul road defects are considered, it appears that mine road-user preference is for much reduced wet skid resistance, dust and dry skid resistance defects. This defines 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 defects are minimized (Area 1, Category I roads). Extending this region to encompass poorer (but nevertheless operable) performance enables an additional area (Area 2, Category II and III roads) to be defined.

The specification stipulates individual parameter limits, but also has predictive capabilities which contribute to an understanding of the consequences when materials outside the specified ranges are used as wearing course materials. If the only materials available for wearing course selection lie outside the parameters limits, a mixture of those materials can be evaluated using the above guidelines. The proposed mix ratio can be used to define a new 'mixed' material specification proportional to the mix ratio, from which Gc and Sp can be derived. In a similar fashion, an existing haul road wearing course can be successfully rehabilitated by adding an appropriate material to restore the mix to specification.

The specifications should also be evaluated in the light of other material property limits identified as important in functional performance but not directly assessed in Figure 3. Table 2 presents a summary of these property limits, together with the type of road defects most often associated with departures from the recommended parameter ranges.



**Figure 3.** Haul road wearing course material selection (Thompson and Visser, 2006)

**Table 2.** Recommended parameter ranges for mine haul road wearing course material selection

Impact on Functionality Below Recommended Range	Material Parameter	Range Min	Range Max	Impact on Functionality Above Recommended Range
Reduce slipperiness but prone to ravelling and corrugation	Shrinkage Product	85	200	Increased dustiness and poor wet skid resistance
Increased loose stones, corrugations and potential tire damage	Grading Coefficient	20	35	Increased ravelling and poor dry skid resistance
Reduced dustiness but loose material will ravel	Dust Ratio	0,4	0,6	Increased dust generation
Increased loose stoniness	Liquid Limit (%)	17	24	Prone to dustiness, reduced ravelling



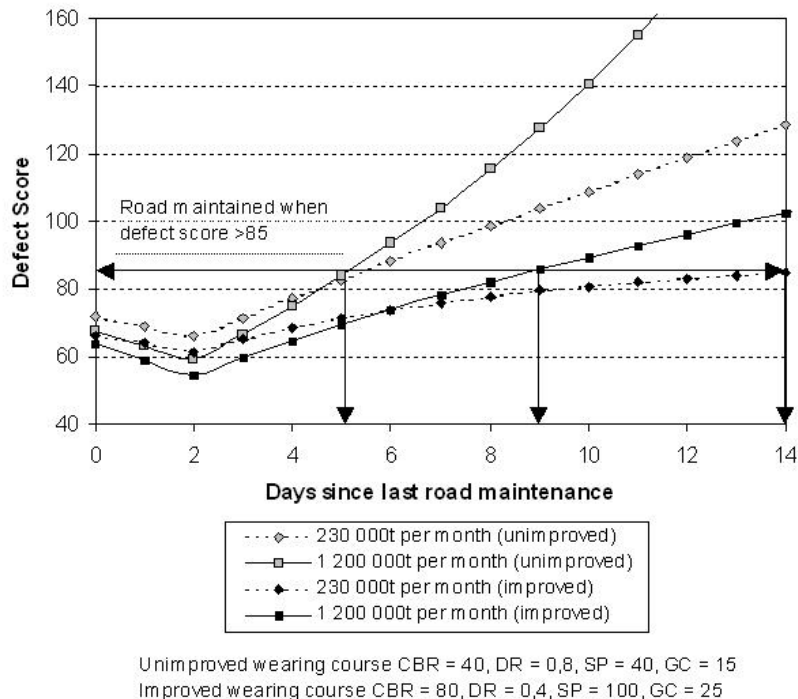
Increased loose stoniness	Plastic Limit (%)	12	17	Prone to dustiness, reduced ravelling
Increased tendency to ravel, loose stoniness	Plasticity Index	4	8	Prone to dustiness and poor wet skid resistance
Poor wet weather trafficability, churning, excessive deformation and cross-erosion. Maintenance intensive	Soaked CBR at 98% Mod AASHTO	80		Increased resistance to erosion, rutting and improved trafficability
Ease of maintenance, vehicle friendly ride and no tire damage	Maximum Particle Size (mm)		40	Poor surface finish following maintenance, potholing and potential tire damage

## 5.1 Haul road wearing course material selection case study

A current haul road wearing course material (Sp 40, Gc 15) lies outside the selection guidelines and is prone rapid deterioration (due mostly to ravelling of the unbound aggregates). Materials that could be used for blending with the current wearing course have high Sp and Gc values. If the wearing course material deterioration is modelled in terms of functional defect score progression variation with the interval between maintaining the road using the models developed by Thompson and Visser (2002, 2006), the unsuitability of the wearing course material is evident from the high defect score and rate of deterioration at low and high traffic volumes (230 and 1200kt/month), as shown in Figure 4 and the frequent re-application of water for dust allaying purposes (0,5 litre/m<sup>2</sup> every 44 minutes).

In order to improve the functional performance of the wearing course at the mine, 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. Figure 4 shows the much reduced functional defect progression rate for the new wearing course when subjected to the same traffic volumes as previously. The mine previously bladed both high- and low-volume roads at 5-day intervals and with the rehabilitation of the road, the blading interval was increased to 9- and 14-days on the roads respectively. With regard to dust allaying, the re-application frequency was reduced to 0,5 litre/m<sup>2</sup> every 60 minutes for the same maximum allowable dust defect score.

Whilst the case study addresses individual functional defects and their control through grader blading or water-car spraying, when considering total haulage costs, the cost components associated with operating the haul truck (fuel, tyres, maintenance parts and labour) and maintaining the road (grader and water-car operating costs) need to be analysed systematically in conjunction with the wearing course material deterioration to determine the optimal frequency of wearing course maintenance commensurate with minimum vehicle operating and road maintenance costs.



**Figure 4.** Predicted reduction in deterioration for new wearing course material mix at 230 and 1200kt/month traffic volumes.

## 6 Haul road maintenance scheduling and management

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

Through the development of a maintenance management system (MMS), the optimum maintenance frequency for each road segment of a mine haul road network can be determined, commensurate with the lowest total vehicle operating and road maintenance costs. Where resource 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 deterioration (roughness progression) and vehicle operating and road maintenance costs.

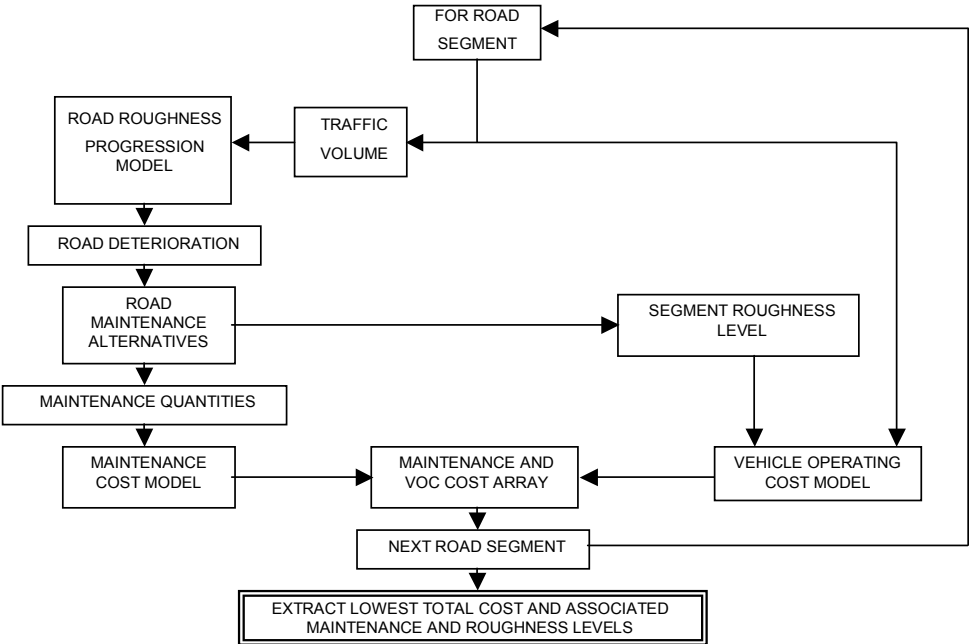
Road roughness progression forms the basis of the MMS since roughness, which impacts on rolling resistance, is the principal measure of pavement condition that can be directly related to both vehicle operating costs and the frequency of maintenance activities. Using the experimental procedure outlined by Thompson (1996), 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 recourse was made to existing models developed for

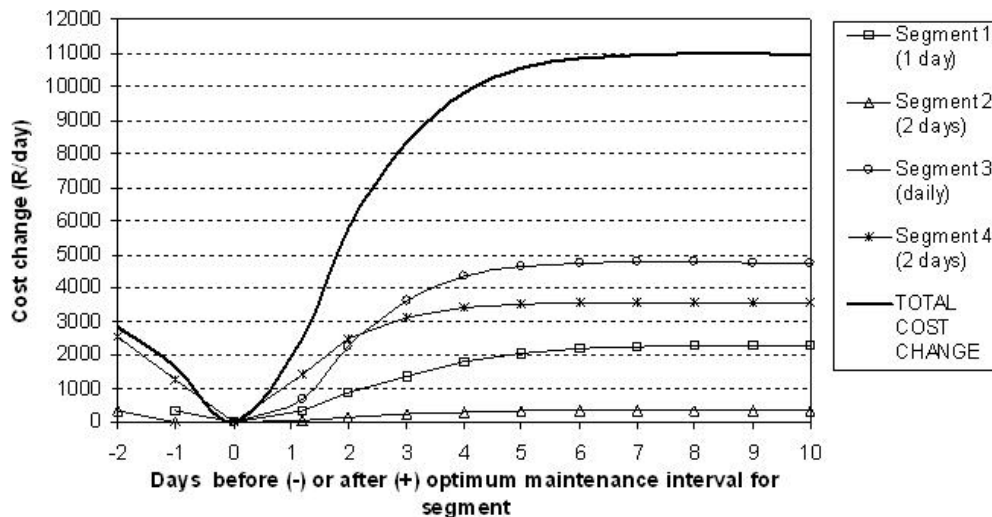
public commercial trucks. Although the parameter ranges were dissimilar to those of mine haul trucks, when coupled with a hypothesis of the influence road roughness and geometry on these cost components, a basic model was developed in each case. These models were then compared with the limited mine data 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. These models are discussed in more detail by Thompson and Visser (2003).

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 analysis approach as shown in Figure 5. 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 maintenance equipment available operating hours.

When analysing the results of individual mine simulations, the actual mine operating practice was seen to closely resemble that predicted by the model, especially with regard to increased maintenance intervals on lightly trafficked roads. A typical result is illustrated in Figure 6 from which it is seen how total vehicle operating costs for this particular operation are minimised at the optimal individual road 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 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.



**Figure 5.** Flow diagram of MMS for mine haul roads (for a single maintenance strategy iteration).



**Figure 6.** Haul road segment and total road-user cost variation with maintenance interval.

## 7 Haul road dust management

Whilst wearing course material selection guidelines together with a MMS approach aim to optimise road performance at minimum total road-user costs, considerable time and expenditure is nevertheless applied to the reduction of the haul road dust defect generated by haul trucks running on a gravel surface. Dust generation from mine roads has been recognised as both a health and safety issue and mines regularly re-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 provides 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 (Thompson and Visser, 2000(a)).

Many products are available which are claimed to reduce both dust and road maintenance requirements for mine roads. Often however, minimal specifications of their properties and no comprehensive comparable and controlled performance trials have been carried out in recognized, published field trials. Additionally, incorrect application techniques and construction methods often result, which leads to considerable scepticism about such products and their overall cost-effectiveness.

The selection matrix in Table 3 can be used to identify classes of palliative which would suit a certain application. However, the data does not specify the level of performance that could be expected, nor the average degree of palliation or degeneration rate expressed in terms of time from initial establishment and re-application rates. This information would be required as a precursor to an economic assessment of the selected palliative benchmarked against the base case of water-based spraying.

A general observation from the study mentioned above was that a poor wearing course material cannot be improved to deliver an adequate performance solely through the addition of a dust palliative. The haul road wearing course material should ideally meet the minimum specifications presented earlier. If not, the inherent functional deficiencies of the material will negate any benefit of gained from using dust palliatives. In road surfaces with too much gravel, dust palliatives do not appear to work effectively, more especially where a spray-on technique is used as opposed to a mix-in. The palliatives do not aid compaction of the surface because of the poor size gradation, nor form a new stable surface. New surface

area is created from exposed untreated material whilst, with a mix-in application, poor compaction leads to damage and ravelling of the wearing course, traffic inducing breakdown of the material and eventual dust generation. With regard to water-soluble palliatives, rapid leaching may be problematic in some climates.

**Table 3.** Preliminary palliative selection matrix for mine haul road applications

	High PI (>10)	Medium PI (>10)	Sand	Wet weather trafficability	Ramp roads	Heavy traffic	Short term	Long term	Spray-on	Mix-in	Maintainable	
<b>Wetting Agents</b>		<input checked="" type="checkbox"/>			<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/> I/R		<input checked="" type="checkbox"/>	
<b>Hygroscopic Salts</b>		<input checked="" type="checkbox"/>				<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/> R	<input checked="" type="checkbox"/> I	<input checked="" type="checkbox"/> M	
<b>Ligno-sulphonates</b>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>				<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/> I/R	<input checked="" type="checkbox"/> SO	
<b>Petroleum Emulsions</b>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/> I	<input checked="" type="checkbox"/> I		
<b>Polymer Emulsions</b>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/> I	<input checked="" type="checkbox"/> SO	
<b>Tar/ Bitumen Emulsions</b>		<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/> R	<input checked="" type="checkbox"/> I	<input checked="" type="checkbox"/> SR	
Notes												
I	-	Initial establishment application				R	-	Follow-on rejuvenation applications				
M	-	Maintain when moist or lightly watered			SO	-	Maintain with spray-on re-application					
SR	-	Maintain with spot repairs										

In compact sandy soils, tar and bituminous -based emulsion products appear effective where leaching of water-soluble products may be problematic. However, in loose medium and fine sands, bearing capacity will not be adequate for the tar/bitumen products to maintain a new surface and degeneration was seen to occur rapidly. Excessive silt or sand fractions may lead to a slippery road whilst poor bearing capacity leads to rutting and the need for road rehabilitation or maintenance, which destroys most products. Small scale potholing has been observed on a number of pavements following spray-on application or re-application, as a result of trafficking lifting fine cohesive material from the road. Again, where no depth of treatment has built up, this will lead to the creation of new untreated surface areas.

In general, spray-on applications do not appear appropriate for establishment of dust treatments, especially with regard to depth of treatment required. A spray-on re-application or rejuvenation may be more appropriate, but only if penetration of the product into the road can be assured, otherwise it will only serve to treat loose material or spillage build-up, which will rapidly breakdown and create new untreated surfaces. A spray-on treatment is however useful to suppress dust emissions from the untrafficked roadsides, since it would be easier (and cheaper) to apply and, with the material typically being uncompacted, would provide some depth of penetration and a reduction in dust emissions from truck induced turbulence.

## 8 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 are often inadequate and the need for improved technologies encompassing the construction and management techniques of mine haul roads, appropriate for the wheel loads of vehicles now in use was recognised. By combining the research and implementation 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.

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 developed, based on the combined effects of traffic type, speed and volumes with 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 and cost the most appropriate palliation option.

The total haul road asset management strategy combining mine layout, construction techniques, available material and road maintenance equipment choice can, through the application of these design and asset management strategies, generate significant reductions in haulage and road maintenance costs whilst achieving optimal asset utilisation in surface mine operations.

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