



# Mine haul road maintenance management systems

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## Synopsis

In surface mining operations, ultra-heavy trucks operate on haul road networks which are typically from 10–40 km in length. These road networks are often not optimally designed and maintained and as a result, identifying and remediating road functional defects is problematic. Most surface mine operators agree good roads are desirable, but find it difficult to translate this into an effective road maintenance system. This paper presents a haul road maintenance management system which utilizes an assessment of rolling resistance based on a functional performance evaluation of a haul road, together with mine haul truck operating cost models to derive the optimal frequency of road maintenance. A typical application is presented which illustrates the potential of the technique to manage maintenance as and where needed with resultant reduction in total road user costs and an improvement in service provided for the road user.

Keywords: Haul road, surface mining, road maintenance, transportation, pavement design

## Introduction

In surface mining operations ultra-heavy trucks hauling payloads in excess of 290 t apply axle loads in excess of 200 t to an unpaved mine haul road, albeit at relatively low daily load repetitions. A mine haul road network typically constitutes a length of 10–40 km comprising a number of road segments, each with variable traffic volumes and construction and material qualities. These road networks have historically been designed and maintained empirically, relying heavily on local experience. Ever-increasing vehicle sizes have resulted in unpredictable road performance, inadequate road maintenance scheduling and excessive total road-user costs. 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 ton material hauled.

There is also the need to balance the cost of any asset against its design life. Empirical road design and maintenance scheduling has

potential for over-expenditure, both on construction, road maintenance and vehicle operating costs, especially in the case of short-term roads. Premature failure and excessive vehicle operating and road maintenance costs, especially in the case of longer-term, high traffic volume roads, are typically the result of under-expenditure on design and maintenance. As tonnage increases and larger haul trucks are deployed, not only would the maintenance costs of existing roads of inadequate design increase, vehicle operating and maintenance costs also increase prohibitively.

The design of mine haul roads encompasses structural, functional and maintenance design aspects as discussed by Thompson and Visser<sup>1,2</sup>. Whilst a strong relationship exists between road structural and functional performance and safe, economically optimal mining-transport operations, the maintenance aspect of haul road design cannot be considered separate from the 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. An optimal functional design will include a certain amount and frequency of maintenance (grading, etc.), within the limits of required road performance and minimum vehicle operating and road maintenance costs.

The use of an appropriate road maintenance management strategy has the potential to generate significant cost savings. Rolling resistance, or road roughness (measured as International Roughness Index (IRI) m/km) is a measure of the extra resistance to motion that a haul truck experiences. It is affected by tyre flexing,

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internal friction and most importantly, wheel load and road conditions. Empirical estimations of rolling resistance based on tyre penetration specify 0.6% increase in rolling resistance per centimetre tyre penetration into the road, over and above the 1.5% (radial and dual assemblies) to 2% (cross-ply or single wheel assemblies) minimum resistance. In addition to tyre penetration, road surface deflection or flexing will also generate similar results, with the truck tyre running 'up-grade' as the deflection wave pushes ahead of the vehicle. For a fleet of Caterpillar 777

(91 t payload, 161 t gross vehicle mass (GVM)) rear dump trucks operating on a 7.3 km 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 reduces by 29% whilst the operating costs reduce by 23%<sup>5</sup>.

The selection of the most appropriate maintenance strategy is the key to realising the economic benefits of reduced transport costs. Haul road maintenance strategies are not widely reported in the literature, nor are they tailored to the complex interactions of the various components in a haulage system. The rolling resistance estimation can be further improved by considering the change in haul road functionality and relating this to changes in rolling resistance. Various types of road maintenance can be carried out on a haul road and this paper reviews these systems prior to introducing the structured maintenance management systems (MMS) for mine haul roads. The MMS is described in terms of the rolling resistance and vehicle operating cost models used to derive the optimized road maintenance frequency for a network of mine haul roads.

### Current state of haul road maintenance management

The ideal maintenance strategy for mine haul roads should be the one that results in the minimum total road-user cost since, in the case of mine haul roads (as opposed to unpaved

roads in the public domain), the agency maintaining the haul road network is also affected by user operating costs. Two elements form the basis of road user costs, namely road maintenance costs and vehicle operating costs (VOC). Both these cost elements are directly related to road condition or more accurately pavement roughness progression—commonly referred to as rolling resistance. The selection of a maintenance programme for mine haul roads should be based on the optimization of these costs, such that total vehicle operating and road maintenance costs are minimized, as shown schematically in Figure 1.

With regard to travel time as a cost element, the value of time is centred around the question of whether or not travel time savings are converted into extra production. Whilst the roughness, or rolling resistance of a mine haul road is a function of traffic volume and wearing course material functional degeneration, it is evident from theoretical vehicle simulation that reduced roughness can significantly increase production (Woodman<sup>3</sup>, Shear *et al.*<sup>4</sup> and Monroe<sup>5</sup>). However, the extent to which a decrease in road roughness achieved through timely road maintenance scheduling, translates practically, as opposed to theoretically into increased production needs to be assessed and confirmed from actual operating experience.

The management and scheduling of mine haul road maintenance has not been widely reported in the literature, primarily due to the subjective and localized nature of operator experience and required road functionality levels. In most cases (Granot *et al.*<sup>6</sup>, Hawkey<sup>7</sup>, Hatch<sup>8</sup>, Taylor and Hurry<sup>9</sup>, and Hustralid and Kuchta<sup>10</sup>) comment is restricted to the various functions comprising maintenance, as opposed to the management of maintenance to minimize overall total costs. Long<sup>11</sup> suggests that adequate serviceability (functionality) can be achieved by the use of one motor grader (and water car) for every 45 000 tkm of daily haulage. The United States Bureau of Mines Minerals Health and

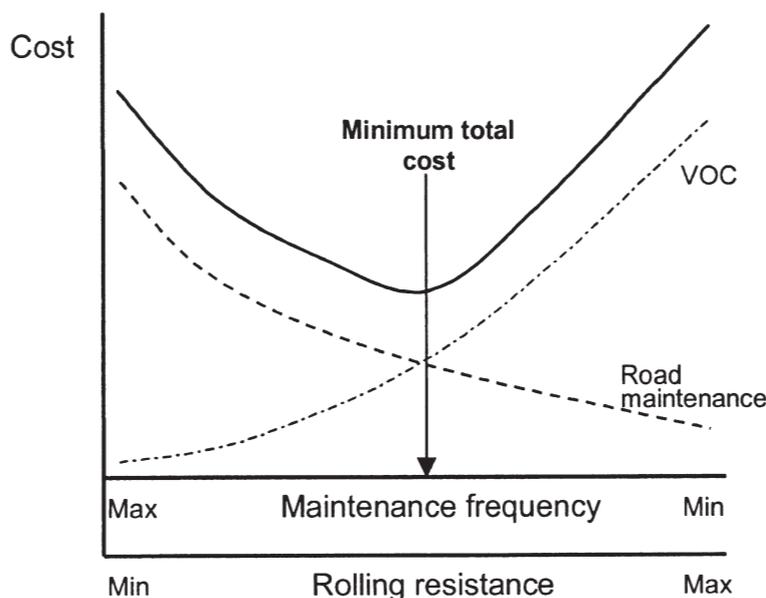


Figure 1—Minimum total cost solution and required road maintenance frequency from vehicle operating costs (VOC) and road maintenance cost considerations

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Safety Technology Division (USBM<sup>12</sup>) in their report on mine haul road safety hazards confirm these specifications, but without a clear statement as to what activities comprise road maintenance.

In addition to the lack of unanimous objectives in applying maintenance, the definition of maintenance as applied to mine haul roads varies from mine to mine. Paterson<sup>13</sup> presented a summary of maintenance activities for unpaved public roads, sub-divided into the categories of routine maintenance, resurfacing, rehabilitation and betterment, as part of a coherent terminology for road expenditures. Table I summarizes these maintenance activities, modified for application to mine haul roads. The routine maintenance category is adopted here to describe the various activities envisaged for haul road routine maintenance. Table II summarizes the various routine maintenance management systems that mines typically apply.

Routine maintenance is carried out on mine haul roads almost daily, depending on the functionality of the road and the traffic volume. The principal goals are;

- To restore the road functionality to a level adequate for efficient vehicle travel with the aim of augmenting productivity and minimizing total road user costs
- To conserve the integrity of the road wearing course by returning or redistributing the gravel surface.

*Ad hoc* or scheduled blading is an inefficient means of road maintenance, with the potential to generate excessive costs due to over- or under-maintenance of the road. Ideally, an optimized approach is required with which to minimize total road-user costs. The maintenance management system (MMS) for mine haul roads has been developed to meet these needs.

*Table I*  
**Maintenance categories and activities for mine haul roads<sup>13</sup>**

Mode	Activity	Effect
Routine Maintenance	Spot regravelling	Fill potholes and small depressions, reduce roughness, exclude water.
	Drainage and shoulder maintenance	Reduce erosion and material loss, improve roadside drainage.
	Dragging	Redistribute surface gravel.
	Shallow blading	Redistribute surface gravel, fill minor depressions and ruts.
Resurfacing	Dust control/watering	Reduces loss of binder and generation of dust.
	Full regravelling	Restore thickness of wearing course.
Rehabilitation	Deep blading	Reprofile road and reduce roughness. Remix wearing course material.
	Rip, regravell, recompact	Improve, strengthen or salvage deficient pavement.
Betterment	Rehabilitation and geometric improvement	Improve geometric alignment and structural strength.

*Table II*

## Routine Mine Haul Road Maintenance Systems

Mode	System	Description
Routine Maintenance	<i>Ad hoc</i> blading	Reactionary maintenance management in response to poor haul road functionality. Typically managed by daily inspection of the road network and a subjective assessment of road segment functionality and maintenance priorities.
	Scheduled blading	Road network is maintained according to a fixed schedule or frequency, irrespective of the actual functionality of the road segment being worked.
	Managed maintenance systems (MMS)	Road network is analysed to determine rate of functional deterioration of individual segments, based on roughness progression, traffic volumes, etc. and segment blading frequency determined to minimize segment and network total road-user costs.
	Real-time road maintenance	Instrumented truck fleet to determine vehicle response to road functionality, both in terms of rolling resistance and individual (isolated) functional defects. Maintenance managed real-time through mine truck dispatch and data management systems.

## Maintenance management systems (MMS)

Optimizing maintenance schedules consists of determining the most opportune frequency at which to maintain a road such that vehicle operating and road maintenance costs are minimized over the whole road network, as illustrated in Figure 1. Thompson<sup>14</sup> found that mine haul road maintenance intervals were closely associated with traffic volumes, operators electing to forgo maintenance on some sections of a road network in favour of others. This implies an implicit recognition of the need to optimize limited maintenance resources to provide the greatest benefit in terms of total maintenance and vehicle operating costs. This optimization approach is inherent in the structure of the MMS developed for mine haul roads (Thompson<sup>14</sup>). Two elements form the basis of the economic evaluation, namely;

- pavement functional performance—roughness (rolling resistance) models
- vehicle operating and road maintenance cost models.

The model is designed for a network of mine haul roads, as opposed to a single road analysis. For a number of road segments of differing functional and traffic volume characteristics, together with user-specified road maintenance and VOC unit costs, the model computes:

- Traffic volumes over network segments over the analysis period (as specified)
- The change in road functionality (as rolling resistance) by modelling
- The maintenance quantities as required by the particular strategy
- The vehicle operating costs (by prediction and modelling)
- Total costs and quantities (including exogenous specified benefits)
- The optimal maintenance frequency for specified segments of the network such that total road-user costs are minimized.

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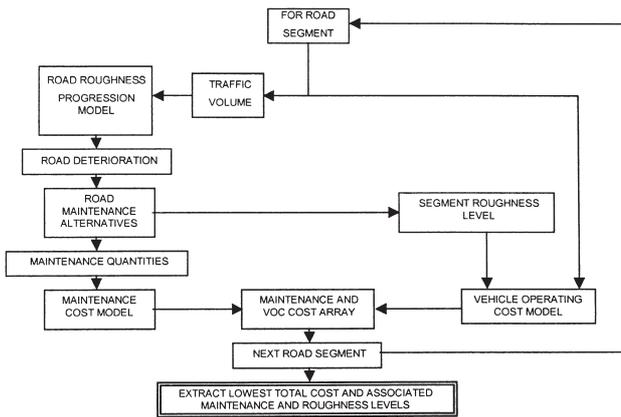


Figure 2—Flow diagram of MMS for mine haul roads (for a single maintenance strategy iteration)

Economic efficiency suggests that tradeoffs should be made between the cost of alternate strategies and the economic return that is derived from lower total transportation costs. In this manner, the maintenance management programme adopted and the associated budget requirements, should be economically justifiable. Figure 2 illustrates the MMS flow chart.

Cost savings associated with the adoption of a maintenance management system approach are dependent on the particular hauling operation, vehicle types, road geometry and tonnages hauled, etc. 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.

## Pavement functional performance—roughness (rolling resistance) modelling

The development of a predictive model for rolling resistance progression with time is critical as a measure of pavement condition that can be directly associated with vehicle operating costs. The rolling resistance at a particular point in time is considered to be a function of the type of wearing course material used, its engineering properties and the traffic speed and volume on the road. These dictate to a large degree the level of functional performance of the road and thus the rate of functional defect generation, which can be equated to the rate of roughness defect score increase, or rolling resistance (Thompson and Visser<sup>2</sup>).

The selection of an appropriate model to describe the relationship between roughness defect score (RDS) and rolling resistance (RR) was based on analysis of the RDS for a number of mine haul road test sections, combined with a theoretical hypothesis of the relationship. The latter was based upon the premise that the rate of rolling resistance increase would decrease at higher levels of RDS. This model is typified by a function having the general form given in Equation [1]

$$RR = RRMIN + RDS \cdot \exp^{(f)} \quad [1]$$

where RR = rolling resistance (N/kg); RRMIN = minimum rolling resistance at (RDS) = 0; f = regression function

describing rate of change in rolling resistance which is a linear combination of independent variables.

Using a logarithmic transformation of the rate of change of rolling resistance (LDRRI), a linear model was developed based on a RDS for the rate of rolling resistance increase. In addition, an expression for the minimum (RRMIN) rolling resistance was sought, based on the independent variable of vehicle speed (V). Equations [2] and [3] present the models for RRMIN at RDS = 0 and LDRRI.

$$RRMIN = \exp^{(-1.8166 + 0.0028 \cdot V)} \quad [2]$$

$$LDRRI = 6.068 - 0.00385 \cdot RDS + 0.0061 \cdot V \quad [3]$$

where V = vehicle speed (km/hr); RDS = roughness defect score (based on degree and extent product of the defect rating for potholes, corrugations, loose material and fixed stoniness<sup>2</sup>).

The model for RRMIN has an R-squared value of 78%, F value of 166.4 which is significant at the 0.1% level for a sample size of 36 and a standard error of the model of 0.191. The model for LDRRI has an R-squared value of 27%, F value of 29.6 which is significant at better than the 2% level for a sample size of 36 and a standard error of 0.146. The full model for rolling resistance variation with RDS is illustrated in Figure 3 together with actual data derived from vehicle coast-down tests at 20, 30 and 40 km/h.

Whilst the models described in Equations [2] and [3] are useful in estimating the rolling resistance of a road at a point in time, it is the rate of change of rolling resistance (i.e. progression) with time or traffic volume that impacts on vehicle operating cost and the maintenance strategy applied. The rolling resistance progression can be derived based on the propensity of a material to generate the RDS defects of potholing, corrugation, rutting, loose material and fixed stoniness by combining functional performance models with road wearing course material parameters.

Such a RDS progression model is illustrated schematically in Figure 4, from which two distinct traffic and material induced actions can be hypothesized. Following maintenance (day 0) there is an increase in RDS due initially to the displacement of loose material, followed by an increase in dynamic loadings imposed on the road together with an increase in abrasion. This causes an accelerating rate of

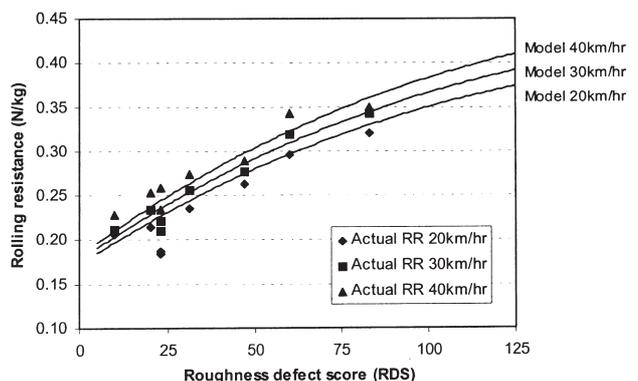


Figure 3—Correlation between actual test data and rolling resistance RDS model

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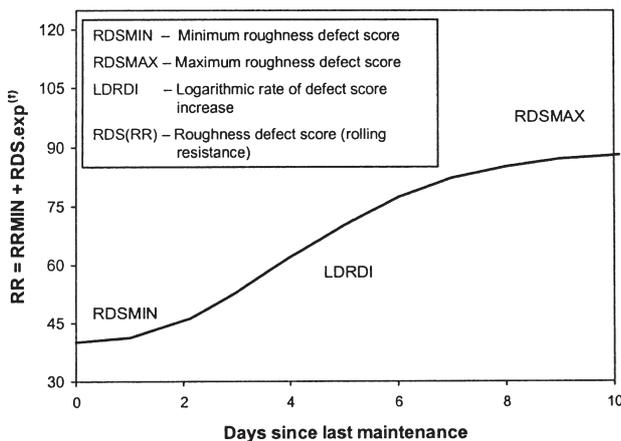


Figure 4—Schematic model for RDS progression

progression until traffic speed slows and wheel paths change to avoid damaged sections. At this level of RDS the progression rate will decelerate to an eventual static level beyond which no further increase in RDS is seen.

This model differs from the functional defect progression model<sup>2</sup> by virtue of the type of defects analysed. The initial decrease in RDS is eliminated since only loose material exhibits a traffic induced reduction in defect score following maintenance, the remaining defects obscuring this isolated post-maintenance decrease.

The selection of a model for RDS progression was based on the aforementioned vehicle and pavement interactions in which a decreasing rate of RDS increase was assumed. This has the general form given in Equation [4] of,

$$RDS = RDSMIN + \left[ \frac{RDSMAX - RDSMIN}{1 + \exp^{(D,f)}} \right] \quad [4]$$

where  $RDSMIN$  = minimum roughness defect score at time ( $D$ ) = 0;  $RDSMAX$  = maximum defect score;  $f$  = Regression function which is a linear combination of independent variables.

Using a logarithmic transformation of  $RDS$ , a defect progression model was developed based on a linear combination of the independent variables for the rate of  $RDS$  increase ( $LDRDI$ ). In addition, expressions for  $RDSMIN$  and  $RDSMAX$  were sought, both assumed to be linear combinations of the independent variables.

The rate of change in  $RDS$  was calculated over a single maintenance cycle in terms of  $LDRDI$  and these values used as the dependent variables in a multiple correlation analysis in order to determine the significant factors affecting defect score progression. For the exponential model of  $RDS$  increase after maintenance, the model given in Equation [5] was found to be significant:

$$LDRDI = 1.768 + 0.001.D \quad [5]$$

$$(2.69KT - 72.75.PI - 2.59.CBR - 9.35.GC + 1.67.SP)$$

where the variables are defined in Table III.

Equation [5] predicts an increase in the rate of  $RDS$  progression for increasing traffic volumes ( $KT$ ), and

Table III

## Independent variables used in the defect score progression models

Independent variable	Description
D	Days since last maintenance
KT	Average daily tonnage hauled (kt)
PI	Plasticity index
CBR	100% Mod. California Bearing Ratio of wearing course material
GC	Grading coefficient, defined as; $\frac{(P265 - P2) \times P475}{100}$ where P265 = percentage of material passing the 26.5 mm sieve P2 = percentage of material passing the 2.0 mm sieve P475 = percentage of material passing the 4.75 mm sieve
SP	Shrinkage product, defined as; $LS \times P425$ where LS = Bar linear shrinkage

shrinkage product ( $SP$ ). The material properties of  $CBR$ ,  $grading coefficient (GC)$  and plasticity index ( $PI$ ) are associated with a reduced rate of increase. The material properties associated with plasticity (in this case  $SP$  and  $PI$ ) are more likely to be associated with an increasing rate of progression. Whilst no multi-collinearity was evident to explain this contradiction in the independent variables it may be hypothesized that whilst highly plastic materials are associated with increasing progression rates (especially if wet), relatively low values of plasticity could result in a decreasing rate (increasing plasticity improving binding up to a point) as evidenced here. The model has an  $R$ -squared value of 52%,  $F$  value of 13.8 which is significant at better than the 1% level for a sample size of 59. For the standard error of the model of 0.589, the approximate 95% confidence intervals for a rate of change in defect score increase of 6 per unit time lie between 1.84 and 19.48.

To establish the minimum RDS immediately after maintenance, an analysis was conducted using  $RDSMIN$  as the dependent variable. The regression rendered the model given in Equation [6].

$$RDSMIN = 31.1919 - 0.05354.SP - 0.0152.CBR \quad [6]$$

The model has an  $R$ -squared value of 62%,  $F$  value of 12.6 which is significant at better than the 1% level for a sample size of 9. For the standard error of the model of 1.73, the approximate 95% confidence intervals for a minimum defect score of 25 lie between 21.54 and 28.46. From the model it is seen that increasing  $CBR$  values result in a lower minimum  $RDS$ . The material shrinkage product ( $SP$ ) also results in a lower minimum score, most probably due to a better surface being produced immediately after maintenance as a result of a more plastic and finer grained wearing course material. Whilst it may be hypothesized that traffic volume may result in a higher minimum defect score due to excessive maximum roughness, the converse has also been observed where higher traffic volumes produce a more compact wearing course than is seen on similar roads subject to lower

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traffic volumes. This result also implies that maintenance temporarily eradicates all traffic-induced roughness defects, hence the prediction of minimum defect score as being a function only of material properties appears reasonable.

The model for maximum RDS is given below in Equation [7].

$$RDS_{MAX} = 7.6415 + 0.4214.KT + 0.3133.GC + 0.4952.RDS_{MIN} \quad [7]$$

The model has an  $R$ -squared value of 90%,  $F$  value of 22.9 which is significant at better than the 0.5% level for a sample size of 9. For the standard error of the model of 1.34, the approximate 95% confidence intervals for a minimum defect score of 35 lie between 32.32 and 37.68. From the model it is seen that increasing daily tonnage ( $KT$ ) representing more accumulated damage, grading coefficient ( $GC$ ) representing deficiencies in binder material (hence corrugation and raveling) and minimum defect score all increase the maximum defect score.

When applied to a typical mine site with an excellent quality of wearing course material, the models faithfully reflect the actual RDS recorded as shown in Figure 5. When these defect scores are converted into rolling resistance values following Equations [2] and [3] it is seen that over a maintenance interval of 5 days, rolling resistance increases from 0.18N/kg to 0.2N/kg at this particular site, equivalent to an additional 0.2% grade resistance. This increase in rolling resistance can be directly associated with an increase in vehicle operating costs, an increase in total costs per ton hauled and increased hauler cycle times. By developing vehicle operating cost models, the effect of increased rolling resistance can be evaluated for fuel, tyres and maintenance parts and labour costs.

### Vehicle operating and road maintenance cost models

The second element of a MMS for mine haul roads is based on modelling the variation of vehicle operating costs with rolling resistance. When combined with a road maintenance cost model, the optimal maintenance strategy for a specific mine haul road, commensurate with lowest overall vehicle and road maintenance costs may be identified.

### Haul truck generic fuel consumption model

The prediction of fuel consumption variation with road roughness is central to any MMS and fuel consumption itself is a significant component of total vehicle operating costs.

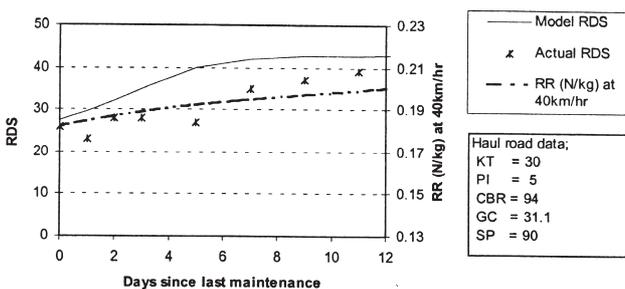


Figure 5—Estimation characteristics of RDS and RR prediction models as applied to a particular mine site

Fuel consumption of vehicles in the public domain has been shown to vary primarily with vehicle type and speed, and the total resistance of the road (Chesher and Harrison<sup>15</sup>).

The analytical approach adopted in determining the contribution of these various factors to haul truck vehicle fuel consumption involved the computer simulation of specific haul trucks to generate a speed model for a range of vehicles commonly used in surface mining. The speed model formed the basis of the fuel consumption model which was derived from vehicle simulations coupled with vehicle torque/fuel consumption maps. The models developed were finally tested in comparison to mine vehicle fuel consumption and average journey time data.

The generic vehicle types chosen for the assessment were rear-dump trucks with a gross power (kW) to gross vehicle mass (GVM) and unladen vehicle mass (UVM) ratio ranging from 4.4–4.9 and 11.1–11.8 respectively. Both electric and mechanical drive options were analysed.

The development of a constant speed fuel consumption model utilized commercial and Original Equipment Manufacturer simulation programs using a set course comprising of acceleration and constant speed sections with differing maximum speed limits applied. The course was modelled with various total resistance (TR) (i.e. grade (GR) plus rolling resistance (RR)) values from -10 to 10%. The consumption model results were found to be broadly similar to those reported for heavy commercial vehicles. Where TR = 0%, a slightly increasing rate of fuel consumption with speed was seen due to dynamic rolling resistance effects. At higher levels of total resistance this effect was largely obscured by the approximately linear increase in fuel consumption with speed. Other work also confirms a similar effect in which the rate of fuel consumption increase with speed for heavier vehicles (albeit from various studies) appears less than for light vehicles and motor cars<sup>15</sup>.

For sections of haul road in which a favourable total resistance exists (i.e. GR + RR < 0%), the associated fuel consumption (FCF) and vehicle speed will be limited by the retarder performance and the effect of total resistance is largely obscured, whilst for sections of road where unfavourable total resistance exists, fuel consumption (FCU) increases with resistance and speed. Thus, two models for fuel consumption are required to fully evaluate a particular haul.

The model derived for fuel consumption where total resistance is unfavourable is given below in Equation [8].

$$FCU = 1.02 + \left( \frac{UVM.V(296.TRU + 4.5.V)}{+L.GVM.V(246.TRU + 0.027.V^2)} \right) \cdot 10^{-5} \quad [8]$$

where  $FCU$  = fuel consumption (ml/s) for unfavourable total resistance;  $GVM$  = gross vehicle mass (t);  $UVM$  = unladen vehicle mass (t);  $V$  = speed of truck (km/h);  $TRU$  = total resistance (unfavourable,  $\geq 0\%$ );  $L$  = truck loading, 1 for laden trucks, 0 for unladen trucks.

The model has an  $R$ -squared value of 64%, a standard error of 39.2 and an  $F$  value of 295 which is significant at better than the 0.001% level for a sample size of 665. The model developed for fuel consumption on favourable total resistance sections is given by Equation [9].

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$$FCF = -3.575 + UVM(0.092 - 0.016.DV) + 0.0017L.GVM \quad [9]$$

where  $FCF$  = fuel consumption (m/l/s) for favourable total resistance;  $DV$  = drive type, 1 for electric drive, 0 for mechanical drive.

The model has an  $R$ -squared value of 81% and an  $F$  value of 394 which is significant at better than the 0.001% level for a sample size of 271. The drive type indicator is included to accommodate the lower fuel consumption associated with unladen electric drive trucks. The models developed were combined to determine the fuel consumption over a particular mine haul road and then compared to actual fuel consumption from mine records. This approach was problematic since operational efficiencies (loader and tip delays, queuing, etc.) precluded meaningful comparison with such data. In the absence of operational data, a validation was carried out against the original simulation program, using mine data to compare the results. The model derived fuel consumption was in broad agreement with the simulation consumptions. Figure 6 illustrates the model developed in terms of the fuel consumption index increase with road grade and RDS.

### Tyre cost model

Numerous tyre cost models exist from studies conducted in Brazil, India, the Caribbean and Kenya<sup>15</sup>. Whilst these relate in part to heavy trucks, these are more typical of vehicles operated on public roads and as such are limited to a GVM of 11–50 t and tyre sizes up to 1100 × 22. Tyre costs are related to tyre wear which involves both abrasive wear of the tyre tread and weakening of the tyre carcass. The option of retreading is not pursued in the case of large mine haul trucks due to the high operating temperature and stresses generated within the tyre.

In the analysis of tyre costs for large haul trucks a number of problems exist relating to the quality of available data. Since a mine has a limited number of roads of variable quality, any model of cost variation with road roughness or other geometric parameters will not be particularly robust. Other limitations exist with regard to damage attributable to loading or dumping areas as opposed to the road itself; up to 70% of tyre damage may occur in loading or dumping areas<sup>16</sup>. This would obscure any road roughness effect on tyre costs.

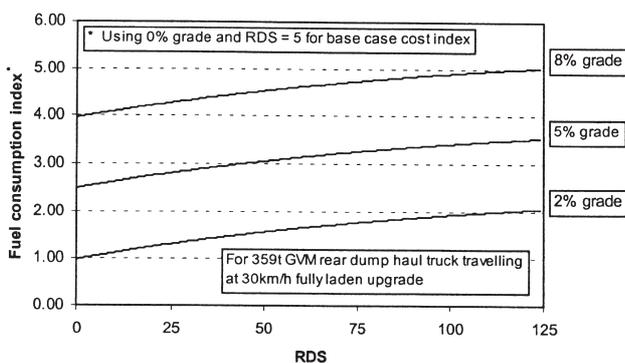


Figure 6—Mine haul truck generic fuel consumption model showing effect of RDS on fuel consumption index

In any MMS model it is the rate of increase of a particular cost item with increasing road roughness which is of major concern as opposed to a fixed cost, although the latter is important in assessing the relative contribution of that cost to total costs. In the absence of suitable data, recourse was made to established models to provide a point of departure in estimating the influence of roughness and geometric parameters on tyre costs. Further research is necessary to assess the validity and transferability of the basic model presented here since only the underlying hypotheses of a roughness- and geometric-related tyre cost relationship can be intuitively deduced, the established model parameter ranges, vehicle types, GVM and tyre types bearing no resemblance to mine haul trucks. The model is given in Equation [10]

$$TW = 0.098 + 0.0015.RDS + 0.002|GR| \quad [10]$$

where  $TW$  = tyre wear (tyres consumed per 1000 km for a 6-wheeled truck);  $GR$  = positive value of road grade (%).

Figure 7 illustrates the application of the model in comparison to existing tyre consumption models for heavy trucks. The model predicts a 30% increase in tyre consumption for a 100% increase in road roughness from a RDS of 27. This equates to an increase in cost of R3.94/km from a cost of R13.87/km, assuming a new tyre cost of R95 000. The effect of road geometry on tyre consumption is modelled as an increase in consumption with grade of road, a 1% change in grade resulting in an extra 1.6% increase in tyre consumption. No curvature effects were modelled since this effect is generally assumed to be insignificant for large trucks.

### Vehicle maintenance cost models

Vehicle maintenance and repair costs comprise both the cost of the parts consumed and the labour hours expended on the repair and maintenance of the vehicle. These costs are related to the type of vehicle, its age, how the vehicle is used and route characteristics. This cost component of the total vehicle operating cost has been shown to be a significant contributor to the benefits from road improvements.

Similar data limitations exist with respect to individual mine parts and labour cost data as with tyre data, with additional complications of costs not being easily ascribed to a particular vehicle type where more than one vehicle type is

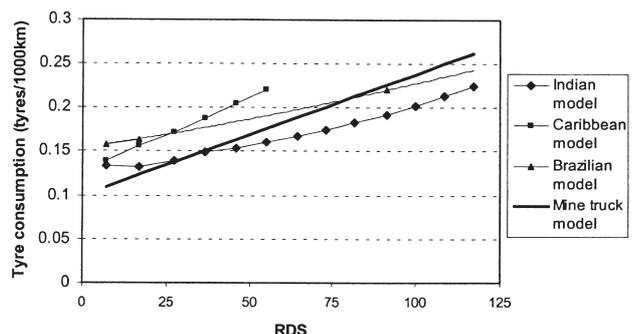


Figure 7—Haul truck tyre consumption model in comparison to existing models<sup>15</sup>

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used for hauling and the influence of high cost long-life replacement parts fitted during the period the model data was collated. The available data do not permit a reliable breakdown of costs on a per vehicle basis and parts consumption history is insufficient to derive suitable weighting coefficients for high cost long-life parts. The analysis, interpretation and transferability of any data generated will be dependent on individual mine maintenance strategies, speeds, loads, driver behaviour, the level of preventive maintenance and the history of the vehicle. It may be anticipated that across mines differences exist in policy and expenditure on maintenance which should ideally be addressed statistically when comparing results.

With these data limitations in mind, recourse was made to established models to provide a suitable point of departure in estimating suitable models for parts and labour costs. Limited data is available with which to corroborate such models but further research is necessary to verify the validity and transferability of the models proposed.

The absence of geometric effects is partially explained by Cheshier and Harrison<sup>15</sup>, speed and load reduction effects being postulated as being the main reason why geometric effects were negligible and poorly determined in these models. In the case of mine haul trucks, load reduction effects are not applicable and the vehicle speed is generally a function of maximum vehicle power and retarder performance as opposed to any driver-applied limit. The majority of haul road networks incorporate unfavourable grade resistance on the laden-haul and, coupled with the greater exploitation of engine capacity on any section of haul irrespective of grade, these effects can be discounted.

The common practice of road user cost studies has been to express the parts consumption in terms of a standard parts cost. This represents the parts consumption as a fraction of the replacement price of the vehicle. The available data were analysed on a fleet, as opposed to a vehicle basis and whilst the resultant model can be seen as applicable to both rear- and bottom-dump trucks, the limitations of this approach (especially with regard to the different vehicle designs and variations in vehicle drive systems) should be borne in mind. Considerable variation in the standardized parts cost was evident and by using these data as a rough guide, a model was developed, described by Equation [11] and illustrated in Figure 8.

$$\frac{P}{VP} = (67.28 + 2.31.RDS)H^{0.375} \quad [11]$$

where  $P$  = parts cost (R/1000 km),  $VP$  = replacement cost of vehicle (R10<sup>5</sup>) and  $H$  = vehicle age (total operating hours) ('1000 hrs).

The model predicts a 48% increase in standardized parts cost for a 100% increase in road roughness from a RDS of 27, given a vehicle age of 7000 hours. In terms of parts cost/km, these roughness and age increase effects represents a cost increase of R6.97/km from R14.52/km for a truck costing R5.4 m.

The approach advocated in the estimation of labour cost involved relating maintenance labour quantity per unit distance to parts consumption per unit distance and highway characteristics, with reference to the Brazilian, Indian and

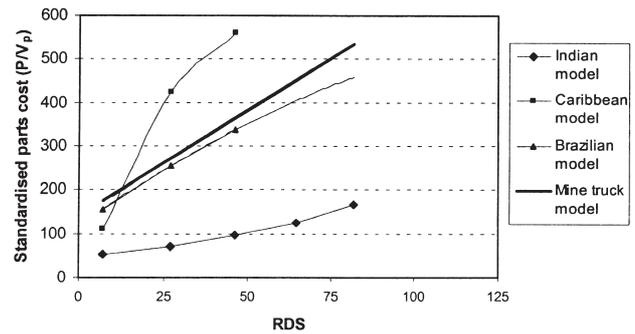


Figure 8—Haul truck parts cost model, using a vehicle age of 7150 hours in comparison to existing models<sup>15</sup>

Kenyan road-user cost studies<sup>15</sup>. Mine truck maintenance labour costs proved to be a difficult item on which to obtain usable information as most mines carried out a combination of in-house, warranty and contractor repairs and no hourly record was kept of the former in the case of individual vehicles or vehicle types in a mixed fleet. Whilst the absence of an hourly labour rate limits the extent to which established models can be used directly (on a cost basis), a basic model could, nevertheless, be derived based on the hypothesized interaction of the dependent variables of standardized parts cost and road roughness as given in Equation [12].

$$L = 220 \left( \frac{P}{VP} \right) 0.45 \quad [12]$$

where  $L$  = Labour costs (R/1000 km)

### Road maintenance cost model

Since total road user costs incorporate both vehicle operating and road maintenance costs elements, the minimization of total costs must incorporate an estimate of road maintenance cost per kilometre. The road maintenance operating cost per kilometre comprises both grader and water car operating costs. Although not contributing directly to a reduction in road roughness, the incorporation of the watering costs in the maintenance costs model is intended to reflect (ideal) operating practice in which, immediately after blading, the section of road is watered to reduce dust, erosion and aid recompaction.

From observation and discussion with operating personnel at surface mines, grader and water-car productivity was theoretically calculated based on a trafficked road width of 24 m, a blade or spray pass-width of 3 and 12 m, maximum vehicle speeds during operation and annual vehicle operating hours. This gave a productivity of 0.75 and 6.25 km maintained road per operating hour for each machine respectively. Whilst no productivity standards have been published with regard to mine haul road maintenance, a figure of between 8–18 km of maintained road per 16 hour day is quoted by mine personnel which is in broad agreement with the theoretically calculated productivity of 0.75 km/hr.

The assumption of a single blade-pass was adopted in this analysis on the basis of observation. However, most operators envisaged an increase in the number of blade-

## Mine haul road maintenance management systems

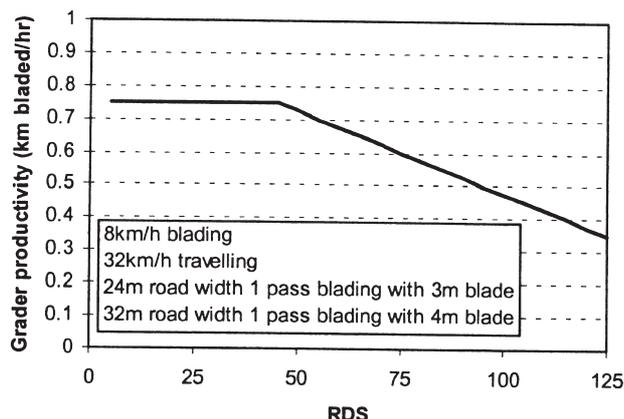


Figure 9—Productivity of a motor-grader during routine haul road maintenance operations

passes required to achieve an acceptable finish when the RDS exceeded 45 (equivalent to 0.3 N/kg rolling resistance). A productivity curve is thus proposed, incorporating this reduction in grader productivity associated with excessively rough roads as shown in Figure 9.

The road maintenance cost model is thus constructed from consideration of the average blade width per pass, road width, RDS before blading, motor-grader productivity curve and hourly cost from which the motor-grader cost per kilometre is found. This cost is then combined with the cost per kilometre of the water-car and workshop costs to produce a total cost per kilometre for road maintenance.

### MMS case study application

The proposed MMS is now applied to a typical surface mine haul road network, to illustrate the interaction and influences of the various models proposed to represent vehicle operating costs, road maintenance costs and the progression of road roughness. The mine hauls 25 kt per day using a fleet of 160 t capacity electric drive rear-dump trucks, whose average age is 7000 hours and replacement price R5.4 m each. The road network is 11 km in length, comprising three segments whose model characteristics are summarized in Table IV. Roads are maintained by a fleet comprising 3 graders and 2 water cars running at an hourly operating cost of R170 and R210 respectively and productivity as determined the basic grader productivity model described earlier.

By modelling the rate of change in RDS for each of the road segments described in Table IV, the lowest total road user cost was found using the cost models described earlier. Road segment 1 returns lowest total costs when it is maintained every 3 days, whilst for segment 2 the optimal interval is every 2 days and for segment 3, daily maintenance is required. Figure 10 illustrates these results in terms of the total and individual segment cost change per day, associated with sub-optimal maintenance intervals (either too frequent—or infrequent maintenance). Segments 1 and 3 are the most expensive segments of the network to operate, showing a cost penalty associated with over-maintenance (segment 1) and under-maintenance (segments 1 and 3). Segment 2 is not that sensitive to sub-optimal maintenance—

Table IV

### MMS case study—road segment data

Segment data	Segment 1	Segment 2	Segment 3
Road segment length (m)	3000	3500	4500
Road width (m)	30	30	34
Grade (% positive against laden)	3	1	1
Average truck speed (km/h)	20	40	30
Average daily tons hauled (kt)	25	5	20
Material type (1 - mix, 0 - ferricrete)	0	0	0
CBR (%)	46	50	162
SP	198	196	82
GC	36.3	21.3	30.1
PI	10	8	4

in this case by virtue of the much lower tonnage hauled, almost horizontal road and ideal wearing course material characteristics. The illustration shows the importance of establishing road performance characteristics as a basis for road maintenance management decisions—in this case, if grader availability was low, it would make more economic sense to forego maintenance on segment 2 since the cost penalty associated with sub-optimal maintenance is much lower for this segment.

In terms of total cost change per day, Figure 10 shows that significant cost-penalties are associated with over- and under-maintenance of the network, between R6 000–R14 000 per day for optimal  $\pm 2$  and  $+6$  days, or 4%–8% of total road-user costs.

When analysing the results of the MMS, actual mine operating practice was seen to closely resemble that predicted by the model, especially with regard to the increased maintenance interval on lightly trafficked roads. Cost savings associated with the adoption of a maintenance management approach are dependent on the particular hauling operation, vehicle types, road geometry and tonnages hauled, etc. The adoption of the MMS model programme for mine haul roads has the potential to generate significant cost benefits when used dynamically, in conjunction with production planning, to optimize mine haul road maintenance activities for particular combinations of wearing course material, traffic volumes and vehicle types.

### Conclusions

The selection of the most appropriate mine haul road maintenance strategy is the key to realizing the economic benefits of reduced transport costs. However, mine haul road maintenance is generally managed subjectively and not tailored to the complex interactions of wearing course functionality, road traffic volumes and vehicle operating and maintenance costs. By considering initially the change in haul road functionality with time and traffic volume, the equivalent change in rolling resistance, road maintenance costs and vehicle operating costs, an appropriate maintenance strategy can be found based on the minimization of these cost elements. Thus, an optimized approach is required with which to minimize total road-user costs and the maintenance management system for mine haul roads has been developed to meet these needs.

## Mine haul road maintenance management systems

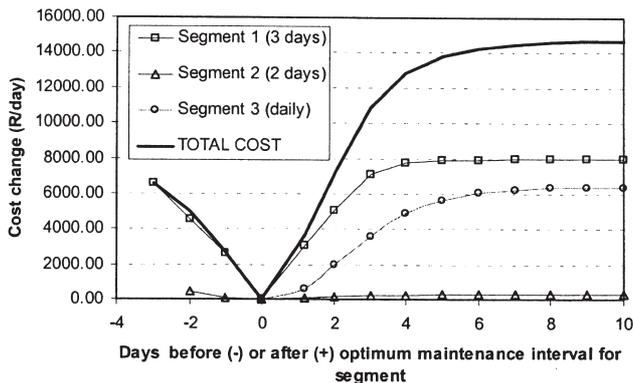


Figure 10—Haul road segment and total road user cost variation with maintenance interval

The development of a predictive model for rolling resistance progression with time served as a measure of pavement condition that can be directly associated with vehicle operating costs. Rolling resistance at a particular point in time was considered a function of the type of wearing course material used, its engineering properties and the traffic speed and volume on the road. The roughness defect score was developed from consideration of the propensity of a material to generate the RDS defects of potholing, corrugation, rutting, loose material and fixed stoniness, by combining functional performance models with road wearing course material parameters.

Vehicle operating cost models of tyre, vehicle maintenance parts and maintenance labour were developed from existing commercial truck models since mine cost data was found to be unreliable. 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.

Total road user costs incorporate both vehicle operating and road maintenance costs and thus the minimization of total costs included a model of road maintenance cost per kilometre. The model was derived from observation and discussion with operating personnel at surface mines and grader and water-car productivity was theoretically calculated at 0.75 km and 6.25 km maintained road per operating hour for each machine respectively, this figure reducing with increasing roughness of the road.

When analysing the results of the MMS as applied to a typical surface mine road network, actual mine operating practice was seen to closely resemble that predicted by the model, especially with regard to the increased maintenance interval on lightly trafficked roads. Cost savings associated with the adoption of a maintenance management approach are dependent on the particular hauling operation, vehicle types, road geometry and tonnages hauled, etc. The adoption of the MMS model programme for mine haul roads has the

potential to generate significant cost benefits when used dynamically, in conjunction with production planning, to optimize mine haul road maintenance activities for particular combinations of wearing course material, traffic volumes and vehicle types.

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