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Mine Haul Road Maintenance Management

By

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"Mine haul road maintenance management"

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Roger Thompson is Professor of Mining Engineering in the Department of Mining Engineering, University of Pretoria, South Africa. He graduated from Camborne School of Mines in 1984 and 1990 with the degrees BSc(Hons)(Mining), MSc(Mining) and gained his PhD through the Department of Civil Engineering at the University of Pretoria in 1996.

Following graduation and as an Anglo American scholarship holder he worked both in underground coal mining and gold mining research and development. In 1991 he took up a post as Senior Lecturer, and from 2003 the post of Professor of Mining Engineering, at the University of Pretoria. His Doctoral studies centred on the design of mine haul roads and associated transportation maintenance and management issues. In 2000, he was guest researcher at the National Institute for Occupational Safety and Health , CDC (NIOSH) – Spokane Research Laboratory and was awarded a Fulbright Scholarship for further study in the United States with both NIOSH and Colorado School of Mines in 2001. Through the University's Business Enterprises Campus Company and in collaboration with Prof Alex Visser, he has undertaken numerous contract research and consulting assignments in southern Africa and internationally, centred on surface mining transportation productivity issues and the provision, rehabilitation or improved design and management of mine haul roads.

He is the co-author of 38 peer reviewed publications in the field of mine haul road design, of which several have received awards from the South African Institute of Civil Engineers and in 2004 he co-authored a paper on integrated mine road maintenance systems that was awarded best paper (Theme 4) at the 6th International Conference on Managing Pavements, Australia.

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His research has focussed primarily on low volume roads and road management systems, particularly elements such as road performance and vehicle operating costs, and issues related to the provision of the road infrastructure in developing regions. In particular he developed a system for scheduling maintenance on a network of unpaved roads based on economic criteria as well as a methodology for determining warrants for upgrading unpaved roads. This research was carried out at the CSIR, at the University of Texas at Austin, and during a US$15 million World Bank study executed in Brazil from 1975 to 1979. More recently he has been involved in developing pavement structures for local access streets and guidelines for paving low volume roads. On the other side of the spectrum he has also carried out research on pavement structures to carry ultra-heavy axle loads such as on open-cast mines and container terminals.

He has consulted with the Governments of Namibia and Chile on road management systems and low volume roads. In the implementation of the haul road technology he has provided advice to a number of mining companies in South Africa, Botswana, Namibia and Indonesia.

In November 1994 he received the best research paper award dealing with the Reconstruction and Development Programme from the Chartered Institute of Transport for a paper published in Concrete/Beton on the application of Hyson-cells to access streets and in 1999 he was the recipient of the Award for Meritorious Research of the South African Institution of Civil Engineering. In 2004 he co-authored a paper on integrated mine road maintenance systems that was awarded best paper (Theme 4) at the 6th International Conference on Managing Pavements, Australia.

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2 Introduction

In surface mining operations a mine haul road network typically constitutes a length of 10-40km 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, 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 & Visser[1,2] . 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 its surrogate, 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, 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[3]. 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 (91t payload, 161t gross vehicle mass (GVM)) rear dump trucks operating on a 7,3km 7% incline, if road rolling resistance is reduced from 8% to 4%, the capital cost of equipment necessary to move 5 million tons per annum reduces by 29% whilst the operating costs reduce by 23% [3].

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 systems is described in terms of the rolling resistance and vehicle operating cost models used to derive the optimised road maintenance frequency for a network of mine haul roads.

3 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 public unpaved roads), 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 specifically pavement roughness progression – commonly referred to as rolling resistance. The selection of a maintenance program for mine haul roads should be based on the optimisation of these costs, such that total vehicle operating and road maintenance costs are minimised, as shown schematically in Figure 1.

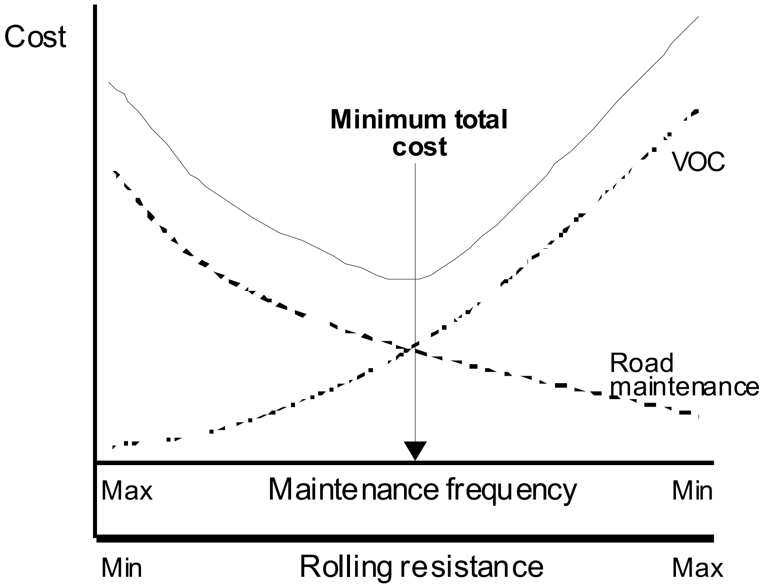


Figure 1 Minimum total cost solution and required road maintenance frequency from vehicle operating costs (VOC) and road maintenance cost considerations

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 that reduced roughness can significantly increase production (Woodman[3], Shear et al[4] and Monroe[5]). 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 localised nature of operator experience and required road functionality levels. In most cases (Granot et al[6], Hawkey[7], Hatch[8], Taylor & Hurry[9] and Hustralid & Kuchta[10]) comment is restricted to the various functions comprising maintenance, as opposed to the management of maintenance to minimise overall total costs. Long[11] suggests that adequate serviceability (functionality) can be achieved by the use of one motor grader (and water car) for every 45 000tkm of daily haulage. The United States Bureau of Mines Minerals Health and Safety Technology Division (USBM[12]) 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. Table 1 summarises what maintenance entails in a mining environment.

Table 1 Maintenance Categories and Activities for Mine Haul Roads (13)

Mode	Activity	Effect
Routine Maintenance	Spot regravelling	Fill potholes and small depressions, reduce roughness, and 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.
	Dust control/watering	Reduces loss of binder and generation of dust.

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 minimising total road user costs
- To conserve the integrity of the road wearing course by returning or redistributing the gravel surface.

Table 2 lists the various means of managing routine maintenance of mine roads. 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 2 Routine Mine Haul Road Maintenance Systems.

System	Description
Ad-hoc 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 (MMS)	Road network is analysed to determine rate of deterioration of individual segments, and segment blading frequency determined to minimise segment and network total road-user costs.

4 Maintenance management systems (MMS)

Optimising maintenance schedules consists of determining the most opportune frequency at which to maintain a road such that vehicle operating and road maintenance costs are minimised over the whole road network, as illustrated in Figure 1. Thompson[14] 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 optimise limited maintenance resources to provide the greatest benefit in terms of total maintenance and vehicle operating costs. This optimisation approach is inherent in the structure of the MMS developed for mine haul roads (Thompson[14]). 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 modeling
- The maintenance quantities as required by the particular strategy
- The vehicle operating costs (by prediction and modeling)
- 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 minimised.

Economic efficiency suggests that tradeoffs should be made between the costs 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.

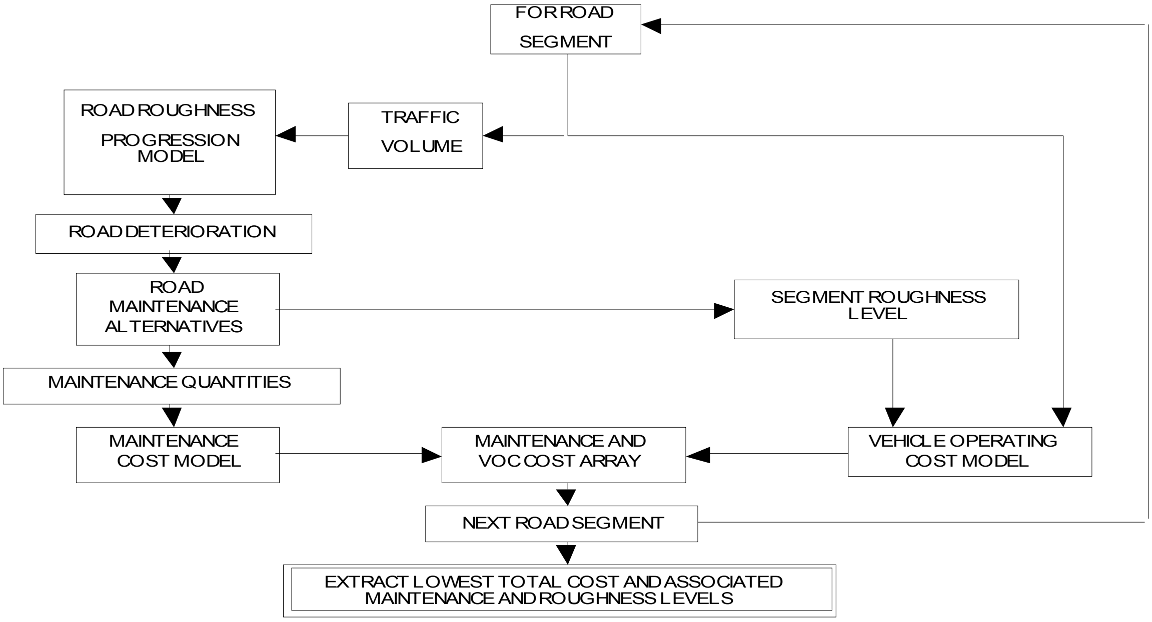


Figure 2 Flow diagram of MMS for mine haul roads (for a single maintenance strategy iteration).

Cost savings associated with the adoption of a maintenance management system approach are dependant 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.

5 COMPONENTS OF MMS MODEL

5.1 Rolling resistance

Rolling resistance is critical as a measure of pavement condition that can be directly associated with vehicle operating costs and is 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 (RDS), or rolling resistance (Thompson and Visser[2]).

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 40km/h from which it is seen how rolling resistance increases with increased road defect score.

Rolling resistance also changes over time or traffic volume. The rolling resistance *progression* can be derived based on the propensity of a wearing course 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.

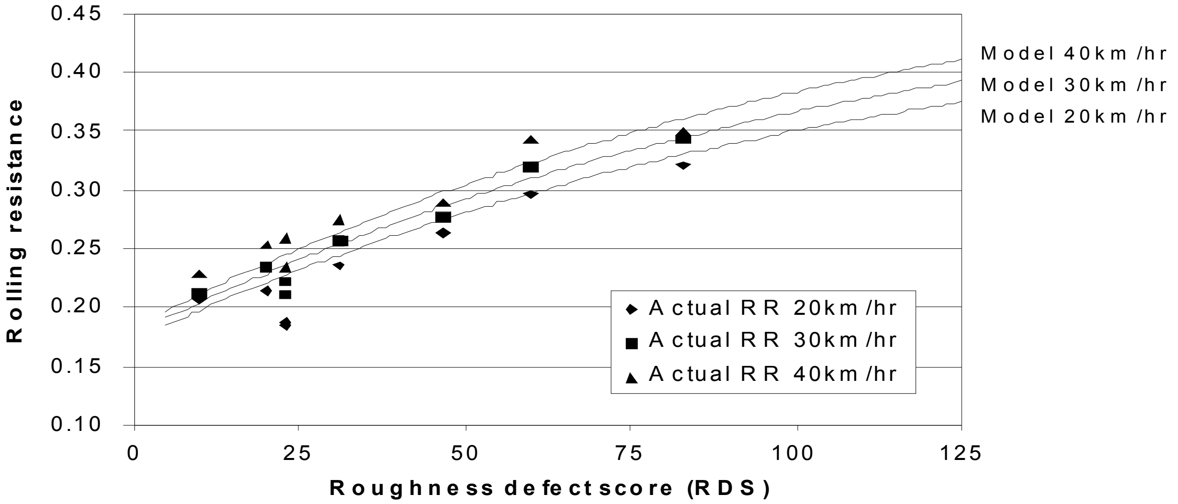


Figure 3 Correlation between actual test data and rolling resistance RDS model

Such a RDS progression model is illustrated in Figure 4, from which two distinct traffic and material induced actions can be hypothesised. 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 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.

Figure 4 Variation of rolling resistance as applied to a particular mine site with excellent wearing course material parameters

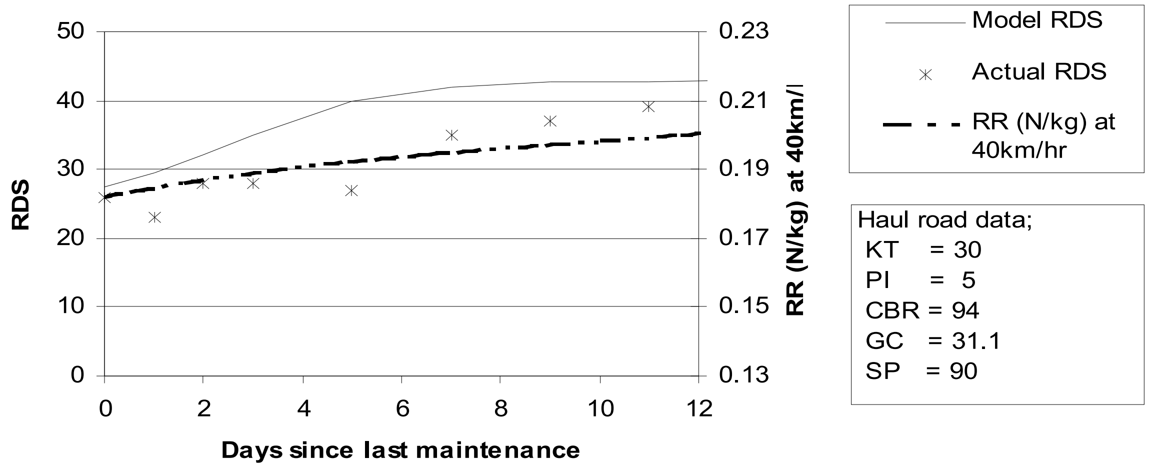


Figure 4 shows that over a maintenance interval of 5 days, rolling resistance increases from 0,18N/kg to 0,2N/kg at this particular site, equivalent to an additional 0,2% grade resistance. This increase in rolling resistance can be directly associated with an increase in vehicle operating costs, an increase 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.

6 Vehicle operating 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.

6.1 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. Fuel consumption of vehicles on public roads has been shown to vary primarily with vehicle type and speed, and the total resistance of the road (Chesher and Harrison[15]).

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.

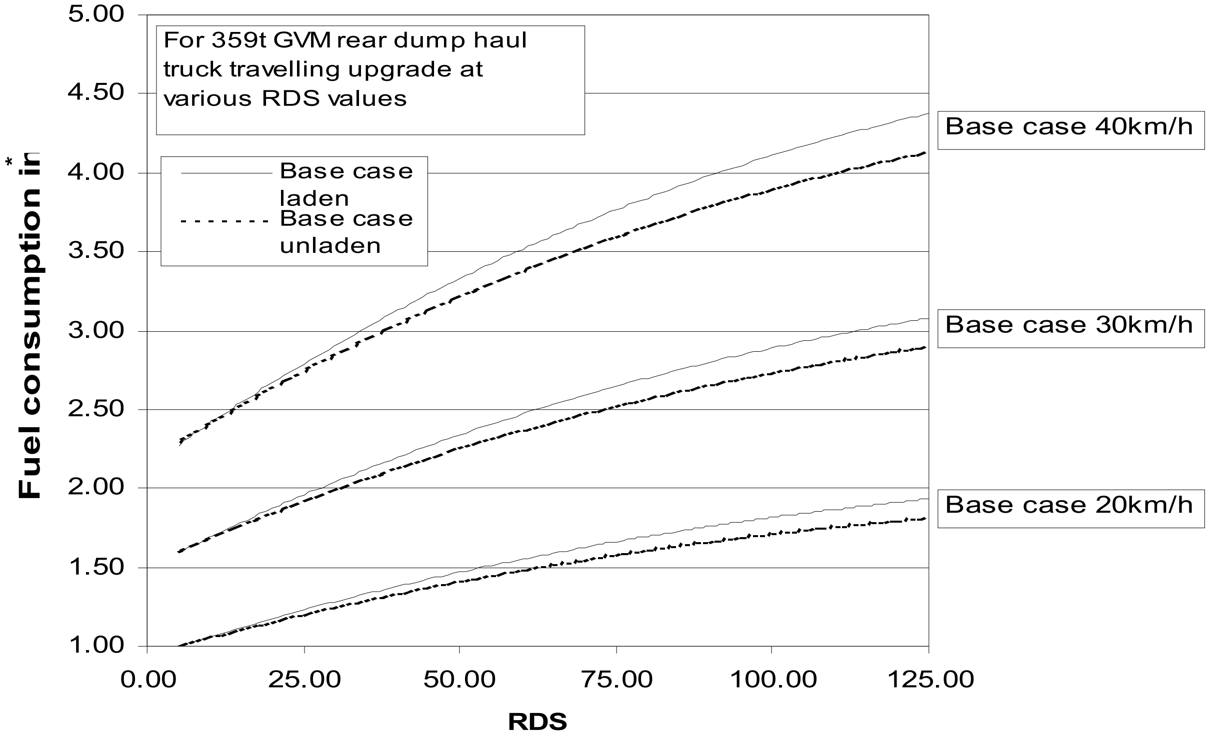
Figure 5 illustrates the model developed in terms of the fuel consumption index increase with road grade and RDS. The fuel consumption index represents the increase in fuel consumption from a base-case RDS of 5 and 0% grade. The index increments for loading, speed and grade increase are given in the Figure. For example, the index increment for a laden truck travelling at 30 km/h up a 5% grade is

(0,74 x 5) = 3.7, and at a RDS of 62 for the base case at 30 km/h, the fuel consumption increase from base case is (3.7 + 2.5) = 6.2.

6.2 Tyre cost model

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[16].

In the absence of suitable data, recourse was made to the underlying hypotheses of a roughness- and geometric-related tyre cost relationships. Figure 6 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.



	Speed (km/h)	20	30	40
Fuel consumption index increment per 1% increase in grade	Laden	0.49	0.74	0.99
	Unladen	0.43	0.65	0.86

Figure 5 Mine haul truck generic fuel consumption model showing effect of RDS on fuel consumption index

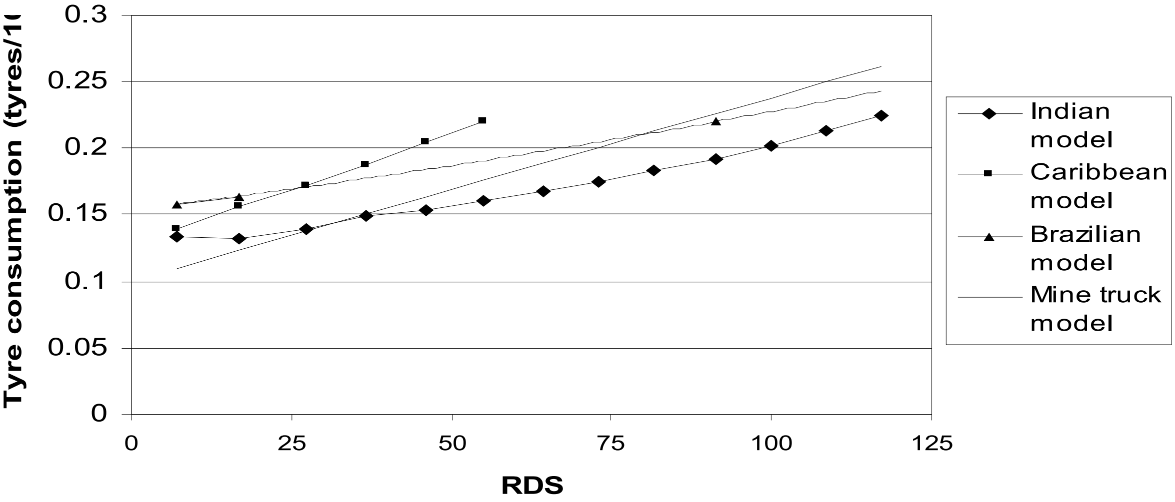


Figure 6 Haul truck tyre consumption model in comparison to existing models[15]

6.3 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 road characteristics. This cost component of the total vehicle operating cost has been shown to be a significant contributor to the benefits from road maintenance management.

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 used for hauling and the influence of high cost long-life replacement parts fitted during the period the model data was collated.

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 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 standardised parts cost was evident and by using this data as a rough guide, a model was developed, as shown in Figure 7, where P = parts cost (R/1000km), VP = replacement cost of vehicle ($R10^5$).

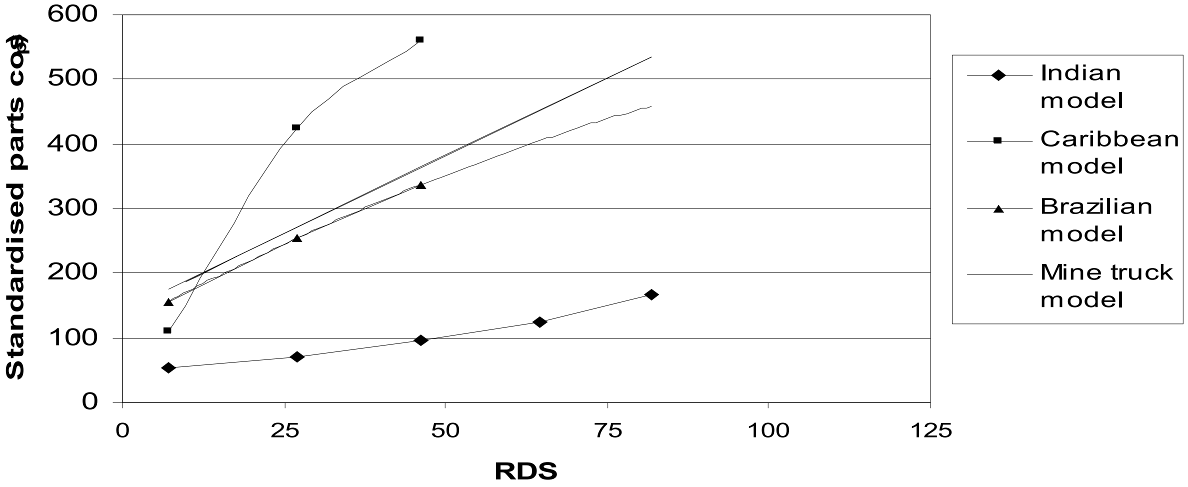


Figure 7 Haul truck parts cost model, using a vehicle age of 7150 hours in comparison to existing models[15]

The model predicts a 48% increase in standardised 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 R5,4m.

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. 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 can be expressed as;

$$L = 220\left(\frac{P}{VP}\right)^{0,45}$$

where L = Labour costs (R/1000km)

7 Road maintenance cost model

Since total road user costs incorporate both vehicle operating and road maintenance costs elements, the minimisation 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 24m, a blade or spray pass-width of 3 and 12m, maximum vehicle speeds during operation and annual vehicle operating hours. This gave a productivity of 0,75 and 6,25km 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 8-18km of maintained road per 16-hour day is quoted by mine personnel which is in broad agreement with the theoretically calculated productivity of 0,75km/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-passes required to achieve an acceptable finish when the RDS exceeded 45 (equivalent to 3% rolling resistance). A productivity curve is thus proposed, incorporating this reduction in grader productivity associated with excessively rough roads as shown in Figure 8.

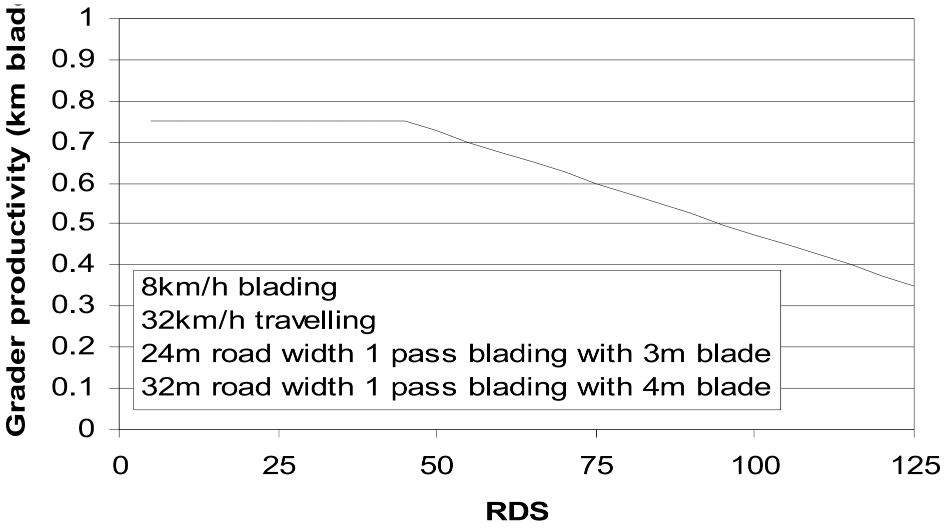


Figure 8 Productivity of a motor-grader during routine haul road maintenance operations.

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.

8 MMS CASE STUDY APPLICATION

The MMS is now applied to a typical surface mine haul road network, to illustrate the interaction and influences of the various costs when road condition deteriorates. The mine hauls 25kt per day using a fleet of 160t capacity electric drive rear-dump trucks, whose average age is 7000 hours and replacement price R5,4m each. The road network is 11km in length, comprising four segments whose model characteristics are summarised in Table 3. A fleet comprising 3 graders and 2 water cars running at an hourly operating cost of R330 and R390 respectively maintains roads and productivity as determined the basic grader productivity model described earlier.

Table 3 MMS case study - road segment data

Segment data	Segment 1	Segment 2	Segment 3	Segment 4
Road segment length (m)	3000	1500	2500	3300
Road width (m)	40	40	30	38
Grade (% positive against laden)	3	4	1	-2.5
Average truck speed (km/h)	20	20	30	50
Average daily tons hauled (kt)	14	11	25	20
Material	Ferricrete	Ferricrete	Mix	Ferricrete

By modelling the rate of change in RDS for each of the road segments described in Table 3, 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 other day, whilst for segment 2 the optimal interval is every 2 days, segment 3 daily and for segment 4, maintenance every second day is required. Figure 9 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 3 and 4 are the most expensive segments of the network to operate, showing a cost penalty associated with over- maintenance (segment 4) and under-maintenance (segments 3 and 4). Segments 1 and 2 are less sensitive to sub-optimal maintenance - in this case by virtue of the much lower tonnage hauled and (in the case of segment 2) almost 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 9 shows that significant cost-penalties are associated with over- and under-maintenance of the network, between R2 700 - R10 900 per day for optimal ±1 and +7 days, or an increase of between 1,4% - 6,2% of total road-user costs per day.

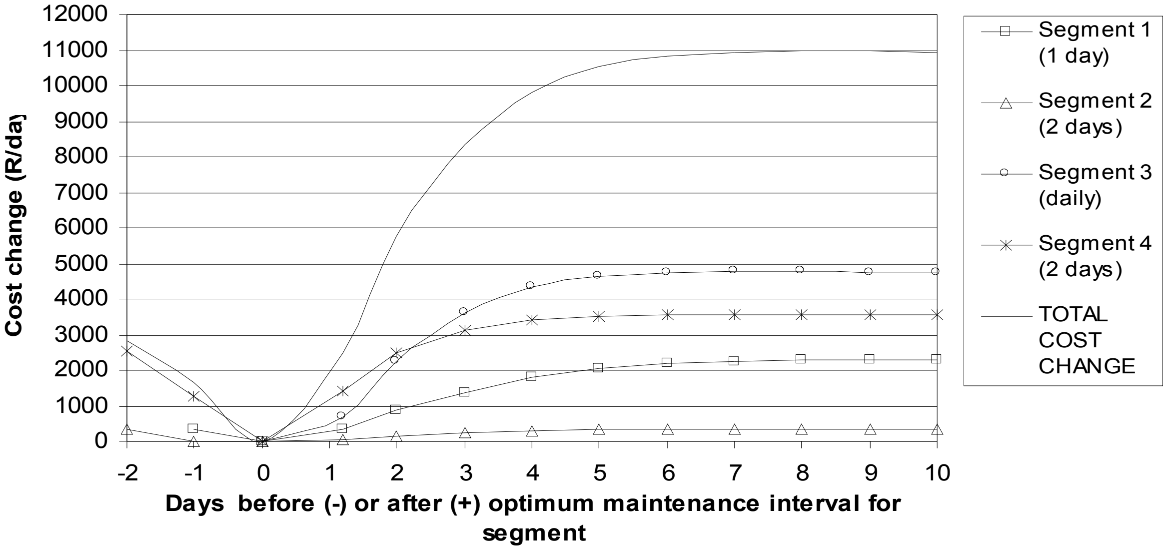


Figure 9 Haul road segment and total road user cost variation with maintenance interval

9 CONCLUSIONS

The selection of the most appropriate mine haul road maintenance strategy is the key to realising 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 minimisation 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.

Cost savings associated with the adoption of a maintenance management approach are dependant on the particular hauling operation, vehicle types, road geometry and tonnages hauled, etc. The adoption of the MMS model program for mine haul roads has the potential to generate significant cost benefits when used dynamically, in conjunction with production planning, to optimise mine haul road maintenance activities for particular combinations of wearing course material, traffic volumes and vehicle types.

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