ABSTRACT
Haul roads are the lifeline of the production system. As such, road problems cause immediate impact on mine productivity and costs. Operations safety, productivity and equipment longevity are dependent on well-designed, constructed and maintained haul roads. Especially with the current tyre and equipment shortages, it is essential to properly maintain haul roads to maximise equipment and tyre life. This paper and the accompanying presentation explores;

- How to determine the best equipment, materials, methods and procedures for road construction based on life of road, usage and location
- How to ensuring proper maintenance of haul roads to increase the life of trucks and tyres
- How to evaluating road maintenance strategies and using road maintenance equipment more effectively
- The use of measuring haul road roughness to reduce damage on trucks and ensure maintenance of control over vehicle

Many mine haul roads are often designed according to empirical rules, relying heavily on local experience. As the trend in increasing truck size continues, the current haul road systems will prove inadequate. Not only would the maintenance costs of existing roads of inadequate design increase, vehicle operating and maintenance costs would also increase prohibitively. An integrated approach to pavement system structural, functional and maintenance design is required which reduces construction, vehicle operating and road maintenance cost components.

INTRODUCTION
A mine haul road network is an asset and should, in conjunction with the haul trucks using the road, be optimally designed and managed. Mine roads have historically been designed empirically, relying heavily on local experience, and this experience, whilst locally relevant, precludes benchmarking, assessment of performance between mine sites and importantly, does not easily allow for ‘what-if’ type evaluations and cost-benefit investigations to be done.

Design and construction costs for the majority of haul roads represent only a small proportion of the total operating and maintenance costs over its operating life. Whilst it is possible to construct a mine haul road that requires no maintenance over its service life, this would be prohibitively expensive, as would the converse but rather in terms of operating and maintenance costs. 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 the road against its design life. Poor designs can result in;

- over-expenditure on construction, especially in the case of short term, low-volume roads (over-designed) where the effect of rolling resistance, although minimised, does not greatly reduce total road-user costs across the mine network of roads
- under-expenditure on construction, leading to premature failure, excessive operating costs and in the case of longer-term, high volume roads (under-designed); high contributory costs from rolling resistance effects.
In the absence of universal, integrated and benchmarkable haul road design, management and performance guidelines, identifying and remediating the cause of poor road performance is problematic.

Rolling resistance 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. 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 290t payload, 498t gross vehicle mass (GVM)) rear dump trucks operating on a 4km 10% incline, if road rolling resistance is reduced from 6% to 2%, the capital cost of equipment necessary to move 30 million tons per annum reduces by 18% whilst the truck operating costs reduce by 16%.

Designing and constructing a quality haul road for optimal performance can only be achieved through an integrated design approach. If one design component is deficient, the other components will 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 downtime and total road-user costs. The cure, however, is not necessarily just ‘more frequent maintenance’; no amount of maintenance will fix a poorly-designed road. Each component must be correctly addressed at the design stage:

- The 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 (curve radius, etc.) and vertical (incline, decline, ramp gradients, cross-fall, super-elevation etc.) plane, stopping distances, sight distances, junction layout, berm walls, provision of shoulders and road width variation, within the limits imposed by the mining method. The ultimate aim is to produce an optimally efficient and safe geometric design and considerable data already exists pertaining good engineering practice in geometric design, suffice to say that an optimally safe and efficient design can only be achieved when sound geometric design principles are applied in conjunction with the optimal structural, functional and maintenance designs.
- 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, caused by deformation of one or more layers in the road.
- A functional design is centred on the selection of wearing course materials; the most suitable choice, application and maintenance strategy is required which minimises functional defects.
- The maintenance design is centred on the optimal frequency of maintenance (routine grading) and thus maintenance can be planned, scheduled and optimised within the limits of required road performance and minimum vehicle operating and road maintenance costs.

For existing operations, which may not have optimally designed and maintained systems, several road infrastructure questions most often arise, typically:

- How do I identify existing deficiencies and quantify their impact and assign priorities within the constraints imposed by limited capital and manpower?
- What will be the impact of new machinery on road performance issues and do I need to plan an appropriate road upgrade?
- How do I assess the impact of various haul road deficiencies in order to identify the safety and economic benefits of taking corrective actions such as more frequent maintenance, regravelling or palliation?

These problems are reflected in the fact that all surface mine operators agree good roads are desirable, but find it difficult to translate this into coherent road management practices. It is necessary to view the management of haul truck and haul road systems holistically, especially with regard to the benefits achieved from the various solutions to enhance productivity. Whilst, for instance, trolley-assist may improve cycle times and reduce costs, it is first necessary to design, manage and maintain the existing road network and hauling fleet optimally before resorting to solutions that do not directly address the key deficiencies – for example high rolling resistance leading to reduced productivity with the existing system. The recommended approach is therefore to assess the extent to which the asset
(the current road network) exhibits scope for improvement and, once optimised, then revert to resource supplementation to leverage these benefits through optimal asset and resource interaction.

Figure 1 illustrates the typical components of a haul road design, whilst Figures 2 and 3 illustrate the approach used to integrate the various design components and enable a problem solving strategy to be applied.

**Figure 1** Typical haul road design components

**Figure 2** Integrated haul road design and management system in outline

**HAUL ROAD GEOMETRIC DESIGN**

In a truck-based haul system, best practice in haul road design, construction and maintenance should be pursued, since these practices are paramount in operating an efficient fleet. The roads themselves should be considered an asset in a similar manner to the trucks that operate on them.

Firstly, a road classification system should be developed, according to traffic volume, vehicle type or permanence (life of road) and performance (or service) levels as part of a mine-wide common framework and design approach. 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.

The next step is then to determine where the road is to be built and its layout – or alignment, both horizontally and vertically. Practically, we often need to compromise between an ideal layout and what the mine geometry will allow. As soon as we move away from the ideal specifications, we must expect road and transport equipment performance to reduce.

The process of geometric design begins with a simple plan, and this plan is improved bit by bit as the specifications are met. The steps are;
Strategic planning and management of fleet and equipment for maximum productivity in the midst of the resources boom

Perth, WA, Australia, 20th – 21st November 2006

Geometric design procedures address:
- Other alignment issues need to be considered to fully specify the horizontal and vertical alignment and
- Safety and good engineering practice require haul road alignment to be designed to suit the braking capacity of the trucks using the road, at the speed limit applied. Additionally, a number of other alignment issues need to be considered to fully specify the horizontal and vertical alignment and layout of a haul road. Geometric design procedures address:

1. **Vertical alignment issues**
   a. **Stopping distance limits of truck** – the manufacturer should confirm the distances required to bring the truck to a stop, following ISO 3450:1996 or local standards.
   b. **Sight distances** – generally at least 150m is required – on a curve or bend in the road, this could be difficult to achieve.
   c. **Optimal and maximum sustained grades** – here we need to build a road with a smooth, even grade, not a combination of grades. Mine trucks work best at grades of about 8-10% uphill (laden) (grade, excluding rolling resistance), so this should be the design specification used.

2. **Horizontal (longitudinal) alignment issues**
   a. **Width of road** – this should allow enough room for two lanes and all the associated safety and drainage features.
   b. **Curvature and switchbacks** – any curves or switchbacks should be designed with the maximum radius possible and be kept smooth and consistent. Changes in curves radii (compound curves) should be avoided. A larger curve radius allows higher safe road speed. If sharp curves or switchbacks are necessary, they will increase haul costs. The dual tyres on drive axles are especially prone to wear going around tight curves. A switchback with an inside depression dug from tyre slip is common and if the depression exposes road base, these rocks will damage the tyre.
   c. **Curve super-elevation (banking)** – this is the amount of banking applied on the outside of a curve to allow the truck to run round at speed. Super-elevations should not exceed 5%. Where tighter curves are required, a speed limit should be applied rather than higher rates of super-elevation.
d. Run-out – this refers to section of haul road used to change from a normal cross-fall or camber into a super-elevated section. The change should be gradual to prevent excessive twisting or racking of the truck chassis. The run out length is typically apportioned 25-33% to the curve and 66-75% to the tangent or run-up to the curve.

e. Cross-slope or camber – a very important concept – it ensures water does not gather and sink into the road. Water on or in a road is extremely bad and every attempt should be made to get water off the road as quickly as possible.

f. Intersection layout - The curve radius of intersections is smaller than that required for maintaining high speed hauling, but should be maximised for non-yield traffic flows. The design of the intersection run-out should be a smooth spiral progression from one cross-fall or camber to the curve super-elevation and out again. Ensure drainage at the side of each intersection leg is adequate to keep water from ponding at the roadside. Where possible, place intersection – or at least non-yield segments – on flat (not inclined) areas.

3. Combined alignment – a few tips when laying out a road with all the factors discussed above:
   a. Avoid sharp horizontal curves at or near the top of a hill. If a horizontal curve is necessary, start it well in advance of the vertical curve.
   b. Avoid switchbacks where possible – but if mine plan dictates their use, make radius as large as possible and place on flat area – NOT on decline
   c. Avoid sharp horizontal curves requiring a (further) speed reduction following a long sustained downgrade where haul trucks are normally at their highest speed. Practically in an open-pit split shell environment this is difficult to achieve, thus visibility towards the curve requiring speed reduction should be unobstructed.
   d. Avoid short tangents and varying grades, especially on multi-lane roads. Grades should be smooth and of consistent grade percentages
   e. Avoid intersections near the crest of vertical curves or sharp horizontal curves. Intersections should be as flat as possible with sight distances being considered in all four quadrants. Where an intersection lies at the top of a ramp, consider 100-200m of level road before the intersection and Avoid stopping and starting a laden haul truck on grade
   f. Avoid intersections with poor drainage. Drainage design at intersections should stop any ponding of water against intersection super-elevated curves.
   g. Avoid sections of road with no camber or cross-fall. Often encountered at curve super-elevation run-in or –out, these flat sections should preferably be at a 1-2% vertical grade to assist drainage

4. Safety berms - a ‘crest’ or road-edge berm will not effectively stop trucks (especially high speed laden or unladen trucks) from leaving the road. At best, they will provide limited deflection and warning to the driver that the truck path needs correcting. The slope of the sides of the safety berm should be preferably 2H:1V to ensure stability and maintenance of height. For a 384TGVM class RDT, this would require a height of at least 2,3m and a base width of at least 4,6m.

5. Ditches and drainage – a well designed drainage system is critical for good roads. Water on the road or in the road layers will quickly lead to poor road conditions.

HAUL ROAD STRUCTURAL DESIGN

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

- How do I determine the thickness of the road above in-situ, so that deflection (rolling resistance) and construction costs are minimised, but performance maximised?
- What will be the impact of new machinery on an existing haul road structural design?
The pavement structure must limit the strains in the sub-grade to an acceptable level and the upper layers must in a similar manner protect the layers below. The main aim here is to reduce surface deflection and deeper deformation to the minimum – thereby reducing rolling resistance.

The design criterion adopted to assess a structural design is that of vertical elastic compressive strain for each layer below the top layer. Various upper limits can be placed on layer vertical strain values, dependent on the envisaged life of the road, traffic volumes and required performance index. Figure 4 illustrates the variation in maximum recommended layer vertical compressive strains for a range of traffic volumes, whilst the Table summarises a typical application to three categories of haul road in terms of maximum strains, traffic volumes and required performance index.

<table>
<thead>
<tr>
<th>Haul Road Category</th>
<th>Description</th>
<th>Typical Performance Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category I</td>
<td>Permanent high volume haul道路 exploit from ramps to ROM tip or waste dumps.</td>
<td>8-10</td>
</tr>
<tr>
<td></td>
<td>Operating life: 10-20 years.</td>
<td>900</td>
</tr>
<tr>
<td>Category II</td>
<td>Semi-permanent high volume ramp or semi-pit roads.</td>
<td>5-6</td>
</tr>
<tr>
<td></td>
<td>Operating life: 5-10 years.</td>
<td>000-1200</td>
</tr>
<tr>
<td>Category III</td>
<td>Semi-permanent medium to low volume in-pit roads.</td>
<td>2-3</td>
</tr>
<tr>
<td></td>
<td>Operating life: under 5 years.</td>
<td>1000-2000</td>
</tr>
</tbody>
</table>

Notes:
1. Based on acceptable structural performance of roads and maximum deflection under fully laden rear wheel, unless 10-resistant performance, 1-nil acceptable poor performance.
2. Using fully laden rear wheel loads for a 4.5kN GVW RDT: For 389 46kN GVW RDT reduces performance index in each category by 1.00.
3. Product of specified performance index and average daily lorry load used to determine design usage.

**Figure 4** Pavement layer vertical compressive strain limits for typical Category I-III haul road structural design.

**Structural Design Case Study**

For comparative purposes, two design options were evaluated; the ‘old’ design method the mine originally used, and the mechanistically designed optimal equivalent, both using identical in-situ and road construction material properties. A 730E Haulpak truck was used to assess the response of the road to applied loads generated by a fully laden rear dual wheel axle.

- How can the mine improve structural performance and reduce rolling resistance?

First and foremost, deflection and deformation must be minimised if rolling resistance is to be minimised. This was achieved by placing a selected blasted sandstone waste rock layer 500mm thick below the wearing course, in place of the previous 350mm layer of plant discard and by reducing the wearing course thickness from 300mm to 150mm. Total layerworks thickness remains the same – but the pavement is stronger and less deflection and deformation occurs.

In the case of the old design, excessive vertical compressive strains were generated in the in-situ material as shown in Figure 5, which leads to high deflections under the tyre (8.8mm) and deformation deeper in the road, thus higher rolling resistance and road maintenance costs. (Note – since much of the deformation is in the in-situ material – no amount of grader blading on top of the road will ‘cure’ this problem). Using the mechanistic design approach no excessive (>2000µε) strains were generated in the structure, primarily due to the support generated by a blasted waste rock base layer, which replaces the previous softer layerworks. This eliminates deformation and minimises surface deflections (3.5mm) and thus also rolling resistance, whilst providing a much less maintenance-intensive road.
Additionally, when using contractor unit costs for layerworks placement and compaction, an 14% variable cost saving is possible when the mechanistic design is used, compared with the old design, by virtue of the reduced material compaction requirements.

As newer, larger haulers enter the market, the question arises whether existing roads can carry the imposed (higher) loads and, if roads are not upgraded, what are the implications in terms of performance and life? The old design will require a rebuild from “top to bottom” – basically by increasing cover or thickness, above in-situ. Using a mechanistic approach, the increase in layer strains can be evaluated against road category, performance and life expectancy, and if necessary, only the waste rock layer need be thickened if warranted. Using a similar approach as to that outlined here, for 385t, 480t and 554t GVM ultra-trucks, construction cost savings of 31%, 41% and 53% are typical when the mechanistic design is used in place of the old design approach, for the construction materials used in this particular example.

**HAUL ROAD FUNCTIONALITY AND DETERIORATION**

The functional performance of a mine haul road is the ability of a haul road to provide an economic, safe and vehicle friendly ride. This is dictated to a large degree through the choice, application and maintenance (blading) of wearing course materials in combination with a structural design of adequate capacity.

Typical questions at this point of the design process are;

- Is my wearing course adequate in terms of;
  - rolling resistance and coefficient of traction?
  - ride quality, dust generation, surface deterioration rates?
  - tyre wear and vehicle damage potential?
  - What options can I consider to reduce rolling resistance and reduce maintenance (blading) costs?

The specifications for wearing course material selection are illustrated in Figure 6. The selection range 1-2 was derived according to mine road-user requirements to reduce wet slipperiness, dustiness, tyre damage potential and dry skid resistance defects, which in turn minimises (but does not totally eliminate) rolling resistance. The specification includes the parameters of shrinkage product and grading coefficient and limits of 85-200 and 20-35 respectively are applied, together with the additional parameters shown in Table 1.

Whilst selection parameters are important, a more critical issue is;

- How does our current wearing course perform?
By analysing and benchmarking the performance of the wearing course, mine operators can determine the practical implications of using a sub-standard wearing course material or blend of materials, in terms of their impact on overall haul road functionality and rolling resistance increase over time. Segments of the haul road network can therefore be designed from a functional perspective to provide similar overall functional performance, albeit with different traffic volumes and material types. This is particularly important in situations where a shortage of suitable wearing course materials exist and priority must be given to using the best road-building materials on high traffic volume (and thus often proportionally higher operating cost) – maintenance intensive roads.

Wearing Course Selection Guidelines

Figure 6  Recommended wearing course material selection ranges for mine haul roads

Table 1 Recommended wearing course material parameter ranges and associated road defects if not satisfied

<table>
<thead>
<tr>
<th>Impact on Functionality Below Recommended Range</th>
<th>Material Parameter Range</th>
<th>Impact on Functionality Above Recommended Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce slipperiness but prone to ravelling and corrugation</td>
<td>Shrinkage Product 85 200</td>
<td>Increased dustiness and poor wet skid resistance</td>
</tr>
<tr>
<td>Increased loose stones and potential tyre damage from large aggregate</td>
<td>Grading Coefficient 20 35</td>
<td>Increased ravelling, poor dry skid resistance, poorly graded aggregate</td>
</tr>
<tr>
<td>Reduced dustiness but loose material will ravel</td>
<td>Dust Ratio 0,4 0,6</td>
<td>Increased dust generation</td>
</tr>
<tr>
<td>Increased loosestoniness</td>
<td>Liquid Limit (%) 17 24</td>
<td>Prone to dustiness, reduced ravelling</td>
</tr>
<tr>
<td>Increased loosestoniness</td>
<td>Plastic Limit (%) 12 17</td>
<td>Prone to dustiness, reduced ravelling</td>
</tr>
<tr>
<td>Increased tendency to ravel, loose stoniness</td>
<td>Plasticity Index 4 8</td>
<td>Prone to dustiness and poor wet skid resistance</td>
</tr>
<tr>
<td>Poor wet weather trafficability, churning, excessive deformation and cross-erosion. Maintenance intensive</td>
<td>Soaked CBR at 98% Mod AASHTO 80</td>
<td>Increased resistance to erosion, rutting and improved trafficability</td>
</tr>
<tr>
<td>Ease of maintenance, vehicle friendly ride and no tyre damage</td>
<td>Maximum Particle Size (mm) 40</td>
<td>Poor surface finish following maintenance, potholing and potential tyre damage</td>
</tr>
</tbody>
</table>
Haul Road Wearing Course Material Case Study

The network selected for the case study was based on several permanent ramp and bench roads in one part of a mine. These segments of road were analysed in terms of functionality, rolling resistance and maintenance requirements and their variation over time or traffic volumes (tons/day).

Figure 6 illustrates the recommended wearing course material selection ranges together with the location of the various road segment wearing course materials available on the mine. The existing unimproved mine road wearing course was reported to be soft, slippery when wet and dusty when dry, as is confirmed from its location in Figure 6. Other materials available on the mine for road building are also shown, the ferricrete material being ideal – but in short supply.

- How can the mine improve wearing course performance and reduce rolling resistance?

Firstly, the functional performance of the various road segments can be modelled or evaluated using a visual scoring system (Appendix 1). Functionality is the sum of road defect scores (e.g. potholing, rutting, corrugations, loose material, dustiness, skid resistance, etc.) determined as the product of degree and extent of 10 functional defects. The maximum defect score is 250 and corresponds to very poor functionality. Figure 7 illustrates the model of existing haul road functionality and how it varies over time – or days between maintenance of road. As would be expected, the less frequently the road is maintained – the higher is the rolling resistance.

![Functional Performance Model](image)

Figure 7 Functional performance variation with days between road maintenance

By considering the materials available for road building and applying similar models, it can be seen from Figure 7 how, for instance, a ‘new’ road built with a ferricrete wearing course has much reduced functional defects (and as will be seen later, reduced rolling resistance). The mine, however, only has a limited supply of ferricrete, so for other, less critical roads, a rehabilitation ‘mix’ of materials can be used with which to improve the performance of these roads. The ideal mix can be determined from Figure 6, simply by combining for instance 30% ferricrete, 20% calcrete with 50% crushed sandstone so the final mix is within the recommended specification range 1.

Additionally, since the functional performance defects of the road can be evaluated, decisions can be made about the most appropriate treatment for these remaining defects. In the case a high shrinkage product material as seen in Figure 7 (representing by linear shrinkage and material smaller than 0.425mm in the wearing course), binding the fines using a palliative treatment will further enhance road performance – but will make little difference to the grading coefficient.

Referring to Figure 8, if the same average level of functionality is required as was seen on the existing (unimproved) road, maintenance can be extended to every 6½-days when using the rehabilitation mix, or every 9-days for the new ferricrete wearing course. (Note that these intervals are sensitive to changes in traffic volumes - if the traffic volumes differ significantly from those modelled, intervals will change).

Whilst the case study addresses wearing course functional defects and their control through grader blading, 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
operate (operating costs) need to be analysed. The analysis is based on the rate of rolling resistance and hence cost increase to determine the optimal frequency of wearing course maintenance commensurate with minimum vehicle operating and road maintenance costs (i.e. total road user costs). This is the essence of maintenance scheduling and management.

![Maintenance interval comparison - functionality](image)

**Figure 8** Maintenance interval comparison with unimproved wearing course

**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, the question arises;

For minimum total road-user costs:
- What maintenance interval should I be using – and how will it vary for each road?
- What maintenance management system is appropriate for my roads?

Routine maintenance or road blading is carried out on mine haul roads almost daily, depending on the functionality and roughness (rolling resistance) of the road and the traffic volume. The principal goals are:
- To restore the road functionality and reduce rolling resistance to a level adequate for efficient vehicle travel with the aim of augmenting productivity and minimising costs
- To conserve the integrity of the road wearing course by returning or redistributing the gravel surface.

Ad-hoc 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 optimised approach is required with which to minimize total road-user costs. The 'systems' approach is the best option to use, where alternative maintenance intervals and the effect on total road-user costs are evaluated. Figure 9 illustrates the concept.

To determine the optimum maintenance schedule, vehicle operating and road maintenance costs are analysed over the whole road network, over time or days between road maintenance. A maintenance management systems (MMS) approach accommodates various combinations of traffic volumes and road segments, and when used dynamically in conjunction with production planning, it has the potential to generate significant cost benefits.
Mine Machine Productivity 2006
Strategic planning and management of fleet and equipment for maximum productivity in the midst of the resources boom
Perth, WA, Australia, 20th – 21st November 2006

Figure 9  Minimum total cost solution and required road maintenance frequency from vehicle operating costs and road maintenance cost considerations

MMS 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 models or user-specified road maintenance and unit vehicle operating cost (VOC) costs, it 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 minimised.

Haul Road Wearing Course Maintenance Management Case-Study

Following from the wearing course case study, road roughness or rolling resistance, comprises the functional defects of potholes, corrugations, rutting, loose material and fixed stoniness. It is these road roughness defects that lead to excessive haulage vehicle operating costs and ideally such defects should be minimised thus minimising rolling resistance.

Rolling resistance can either be modelled from functional performance, or determined from the visual scoring system (Appendix 1). Figure 10 shows how rolling resistance varies for the unimproved, rehabilitated and new (ferricrete) wearing course materials mentioned previously.

Figure 10  Rolling resistance variation with road maintenance interval
As can be seen, both the ‘new’ and rehabilitation mixes result in a 1% reduction in rolling resistance over a 10-day maintenance interval – or a 0.5% increase in rolling resistance from the minimum of 1.7%. From Figure 10, it may seem the best approach is to maintain or blade the haul roads on a daily basis, to keep rolling resistance – and hence VOC - as low as possible. But this solution may incur high road maintenance costs, thus an optimised maintenance interval needs to be found based on total road-user costs, not just truck VOC or road maintenance costs in isolation.

For this case study, a number of road segments from the whole network were selected and evaluated in terms of how they influence total road-user costs. Obviously, the more a segment exercises an influence over total costs, the more frequently it will need to be maintained. If a segment, by virtue of its wearing course material and/or traffic volumes exercises little influence on total costs, we can safely reduce maintenance on this segment in favour of more cost-sensitive road segments.

Using this concept, the MMS takes estimates of the effect of rolling resistance increases on the costs of fuel, tyres, truck maintenance parts and labour, established from the data shown in Figure 11 (roughness defect score (RDS) can be converted to rolling resistance using the graph in Appendix 1). What is critical here is not so much the actual cost, but the relative increase in costs with rolling resistance. This approach allows road network segments to be ranked in terms of their overall contribution to total costs and, from a maintenance management perspective, allows us to see the relative changes, as shown in Figure 12.

Figure 11 Variation in vehicle operating cost components of fuel, tyre, parts and labour with road roughness defect score (RDS)

Figure 12 shows how each of the various road segments can influence VOC if they are over- or under-maintained. The S-ramp road requires daily maintenance to keep cost-increases to a minimum, the bench 2 (B02) segment requires 1-day between maintenance, similarly the B05 segment 3-days between and the B03-04 segments 3½-days between.

The case study 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 B02 since the cost penalty associated with sub-optimal maintenance is much lower for this segment. It would be preferable to concentrate grader maintenance on the S-ramp and, if the recommended maintenance intervals requires further extension, segment B04, to minimise the cost penalty associated with under-maintenance of the network of roads.
Figure 12 Variation in total-costs with maintenance interval, for a number of haul road segments analysed using an MMS methodology

In the longer-term, the models presented can be used as a basis for repair or rehabilitation decisions and haul road improvement strategies. By identifying the specification parameter- and performance-deficiencies of the wearing course, in terms of functionality and rolling resistance or roughness progression rates, segments of the network can be selected for upgrade based on the costs of repair measured against the benefits derived from total road-user cost reduction over the operating life of the segment.

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. Typically, the cost-penalty associated with over- or under-maintenance of the network roads has been seen to vary by between 2% - 16% of total road-user costs per day.

REAL-TIME MAINTENANCE MANAGEMENT SYSTEMS

Whilst the MMS can be applied relatively easily over a road network in which individual segment changes are applied over a period of time (typically, hauling from another ramp, change of tonnage hauled between ramps, etc.), for complex road networks where material is sourced and hauled from a large and highly variable number of loading points, the MMS becomes onerous. These deficiencies can be addressed through real-time truck-road interaction monitoring - specifically the integration of haul truck on-board data with communication and truck location systems.

In its simplest form, a near-real-time system can be developed using visual road network inspections at the start of shift according to the forms given in Appendix 1 and three levels of scoring – green=ok, yellow=need maintenance soon and red=immediate maintenance required. If necessary, the decision as to where to assign maintenance assets can be evaluated by applying weightings to each segment, derived for instance from data similar to that in Figure 12 – showing the road where the most immediate cost-benefit from a maintenance intervention will be seen.

A real-time system is also under development using truck-generated road ‘condition-triggers’ in which the truck interacts with the road to enable the type of defect in the road, and its location, to be recognised. This is based on the integration of truck on-board vital signs data monitoring with the on-board hub, to provide quantitative information on the effects of haul road functionality on truck performance and to identify, manage and remediate sub-standard sections of road across the network. The developmental system is illustrated in Figure 13, showing how existing communication, location and truck monitoring systems are integrated and the information from the system applied in making road maintenance decisions. Where several haul routes are used concurrently, by analysing the road traffic volume and trigger event maps, priorities and locations for road repair can be assigned based on cost-benefit and vehicle damage potential.
CONCLUSIONS

To take full advantage of the use of ultra-heavy haul trucks for the transport of material on surface mines and to operate these vehicles at minimum cost, an integrated road design and management strategy for a network of mine haul roads is required.

Initially, it is important to view the management of haul truck and haul road systems holistically, especially with regard to the benefits achieved from the various solutions to enhance materials handling productivity. Whilst, for instance, trolley-assist may improve cycle times and reduce costs, it is first necessary to manage and maintain the existing road network and hauling fleet optimally before resorting to solutions that do not directly address the key deficiencies of the existing system. The recommended approach is therefore to assess the extent to which the asset (the current road network) exhibits scope for improvement and, once optimised, then revert to resource supplementation to leverage these benefits through optimal asset and resource interaction.

Using a mechanistic structural design methodology can reduce rolling resistance by minimising deflection and deformation of the road structure beneath the vehicle wheels. 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 rolling resistance change.
with time. This 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 can be used as an aid in identifying the most appropriate haul road maintenance schedule commensurate with minimum total road-user costs. Through the application of these design tools and management strategies, mine operators can significantly enhance the performance of the materials handling system and achieve a reduction in haulage and road maintenance costs whilst achieving optimal asset utilisation.

FURTHER READING


Thompson, RJ & Visser, AT. Integrated real-time mine haul road maintenance management with mine wide asset location and communication systems. 6th International Conference on Managing Pavements (ICMP6), Brisbane, Queensland, Australia, October 2004, CD paper 4/9


Appendix 1 On-Site Evaluation Of Wearing Course Functionality And Rolling Resistance

This is based on rating the wearing course on a section of haul road according to:
- How much is affected (the ‘extent’) by the particular defect, on a scale of 1-5
- How bad is the particular defect (the ‘degree’), on a scale of 1-5

If you multiply ‘extent’ x ‘degree’ then you have the ‘defect score’ and if this exceeds the maximum allowed on the acceptability chart or the recording form, maintenance is usually required.

The same process can be repeated for rolling resistance too – but in this case we only assess a few defects – not all the defects – that relate to rolling resistance. Use the same form, but sum the product of degree and extent for roughness defects only and read off from the rolling resistance graph.

<table>
<thead>
<tr>
<th>DEFECT</th>
<th>DEGREE (1-5)</th>
<th>EXTENT (1-5)</th>
<th>DEFECT SCORE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potholes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrugations</td>
<td></td>
<td></td>
<td>1*</td>
</tr>
<tr>
<td>Rutting</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loose material</td>
<td></td>
<td></td>
<td>5*</td>
</tr>
<tr>
<td>Stoniness - fixed</td>
<td></td>
<td></td>
<td>7*</td>
</tr>
<tr>
<td>Dustiness</td>
<td></td>
<td></td>
<td>3*</td>
</tr>
<tr>
<td>Stoniness - loose</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cracks - longit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cracks - slip</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cracks - croc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skid resistance - wet</td>
<td></td>
<td></td>
<td>9*</td>
</tr>
<tr>
<td>Skid resistance - dry</td>
<td></td>
<td></td>
<td>9*</td>
</tr>
</tbody>
</table>

**TOTAL FUNCTIONALITY SCORE**
\( \sum (\text{Defect degree} \times \text{defect extent}) \)

**TOTAL ROUGHNESS SCORE (RDS)**

Refer to graph for rolling resistance percentages

**ESTIMATED ROLLING RESISTANCE (%)**

**Comments**

<table>
<thead>
<tr>
<th>Drainage</th>
<th>On road</th>
<th>Side of road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erosion</td>
<td>Longitudinal</td>
<td>Cross</td>
</tr>
</tbody>
</table>
Functional performance acceptability criteria (example only – you may wish to use other defect score limits)

<table>
<thead>
<tr>
<th>Defect</th>
<th>Haul road defect score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skid resistance dry</td>
<td></td>
</tr>
<tr>
<td>Skid resistance wet</td>
<td></td>
</tr>
<tr>
<td>Cracks -crocodile</td>
<td></td>
</tr>
<tr>
<td>Cracks -slip</td>
<td></td>
</tr>
<tr>
<td>Cracks -longitudinal</td>
<td></td>
</tr>
<tr>
<td>Stones -loose</td>
<td></td>
</tr>
<tr>
<td>Stones -fixed</td>
<td></td>
</tr>
<tr>
<td>Dustiness</td>
<td></td>
</tr>
<tr>
<td>Loose material</td>
<td></td>
</tr>
<tr>
<td>Rutting</td>
<td></td>
</tr>
<tr>
<td>Corrugations</td>
<td></td>
</tr>
<tr>
<td>Potholes</td>
<td></td>
</tr>
</tbody>
</table>

- Desirable
- Undesirable
- Unacceptable

Rolling resistance evaluation

- 5km/h
- 10km/h
- 15km/h
- 20km/h
- 25km/h
- 30km/h
- 35km/h
- 40km/h
- 45km/h

Roughness defect score vs. Rolling resistance (%) graph
General Description of Haul Road Extent Classification

<table>
<thead>
<tr>
<th>EXTENT</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Isolated occurrence, less than 5% of road affected</td>
</tr>
<tr>
<td>2</td>
<td>Intermittent occurrence, between 5-15% of road affected.</td>
</tr>
<tr>
<td>3</td>
<td>Regular occurrence, between 16-30% of road affected.</td>
</tr>
<tr>
<td>4</td>
<td>Frequent occurrence, between 31-60% of road affected.</td>
</tr>
<tr>
<td>5</td>
<td>Extensive occurrence, more than 60% of the road affected.</td>
</tr>
</tbody>
</table>

General Description of Haul Road Degree Classification

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>VISUAL DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Degree 1</td>
</tr>
<tr>
<td>Potholes</td>
<td><img src="image1" alt="Potholes" /></td>
</tr>
<tr>
<td>Corrugations</td>
<td><img src="image4" alt="Corrugations" /></td>
</tr>
<tr>
<td>Rutting</td>
<td><img src="image7" alt="Rutting" /></td>
</tr>
<tr>
<td>Loose material</td>
<td><img src="image10" alt="Loose material" /></td>
</tr>
<tr>
<td>Dustiness</td>
<td><img src="image13" alt="Dustiness" /></td>
</tr>
<tr>
<td>CHARACTERISTIC</td>
<td>VISUAL DESCRIPTION</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Stoniness - fixed in wearing course</td>
<td></td>
</tr>
<tr>
<td>Cracks - longitudinal</td>
<td>None</td>
</tr>
<tr>
<td>Cracks - slip</td>
<td></td>
</tr>
<tr>
<td>Cracks - crocodile</td>
<td></td>
</tr>
<tr>
<td>Skid resistance - wet</td>
<td></td>
</tr>
<tr>
<td>Skid resistance - dry</td>
<td></td>
</tr>
<tr>
<td>Drainage on road</td>
<td></td>
</tr>
<tr>
<td>Drainage at roadside</td>
<td></td>
</tr>
</tbody>
</table>