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Contributions From Improved Surface Mine Haulage Road Design, Operation and Management Techniques To Sustainable Development

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ABSTRACT

Operating well designed and maintained surface mine haul roads is the key to minimising truck haulage costs – in itself a significant component of the total cost per tonne mined. Existing and proposed mining operations are subject to scrutiny, both from the economic and environmental perspectives. In the long run, this scrutiny returns improved efficiencies and leaner, ‘greener’ operations. The focus of this evolving evaluation process should and will certainly fall on haulage operations – simply by virtue of their contribution to overall cost of operations and sustainability impacts. Whilst the end result - improved efficiency and contributions to resource sustainability – is not in itself problematic, it is the route, or process followed to achieve these improvements that needs to be carefully managed. We can be guided on this journey by our understanding of how a road is designed, and, critically, the technological solutions that can contribute to a company’s sustainability initiatives.

This paper examines the current state of mine road design and operation, together with the economic and environmental issues associated with under-performance. The paper serves as a basis for evaluating the economic and environmental contributions that technology in road design and management can deliver to sustainable operations. Utilising innovation is the key to long-term sustainability and as a means of positioning the industry for the imminent structural changes to the economy and environment, changes which are now within the operating life of many mines, haul roads and haul trucks.

Keywords: Surface mining, haul road design, haulage, sustainability indicators

INTRODUCTION

Mining and sustainable development (SD) is often viewed with a good deal of scepticism, since to many, sustainably developing non-renewable mineral resources is a contradiction (Rajaram et al. 2005). In broader terms however, the World Commission on Environment and Development (WCED, 1987), or the ‘Brundtland Commission’ definition; namely ‘...*development to meet the needs of the present without compromising the ability of future generations to meet their own needs*’ is commonly adopted. Although this is a somewhat open definition, in the context of mining, specific SD principles were drafted by the international minerals community in 2003 (ICMM 2003):

- Implement and maintain ethical business practices and sound systems of corporate governance.
- Integrate sustainable development considerations within the corporate decision-making process.
- Uphold fundamental human rights and respect cultures, customs and values in dealings with employees and others who are affected by our activities.
- Implement risk management strategies based on valid data and sound science.
- Seek continual improvement of our health and safety performance.
- Seek continual improvement of our environmental performance.
- Contribute to conservation of biodiversity and integrated approaches to land use planning.

- Facilitate and encourage responsible product design, use, re-use, recycling and disposal of our products.
- Contribute to the social, economic and institutional development of the communities in which we operate.
- Implement effective and transparent engagement, communication and independently verified reporting arrangements with our stakeholders.

How do the ICCM principles translate into a business culture in which performance is measured by financial benchmarks? Sustainability is evolving into a reporting prerequisite, similar to health and safety and as result, sustainability initiatives need to be integrated into operational planning. The challenge, however, is how to provide realistic, long-term sustainability solutions that can be developed and implemented in the short-term.

Mine Haulage and Sustainable Development

The haul road design and subsequent road management and maintenance forms a principal component of the transport operation in surface mines. Transportation of both the mineral product and associated waste is, in itself, a significant cost item in terms of total cost of production. Truck haulage costs can account for up to 50% of the total operating costs incurred by a deep open-pit operation and any savings generated from improved road design and operation have benefits that extend well-beyond company profitability, into the broader issues of sustainable development.

The contributions to a sustainable mining industry that can be derived from focussing on the mine haulage component of the mining cycle are critical and central to many SD reporting strategies. Typical SD reports encompass specific targets relating to;

- energy consumption
- water consumption
- green house gas emissions (GHG)
- safety and innovation

and it is these areas that improvements in haulage system design and management can contribute positively to long-term sustainability solutions, in a relatively short-term implementation timeframe. Short-term value can clearly be derived from reduced energy, water and safety-incidents associated with mine haulage, whilst any costs associated with GHG emissions levied in the future also leverage longer-term benefits.

Kogel *et al* (2009) emphasises the importance of quantifying environmental impacts throughout the mining lifecycle. His survey of various publications concluded that there were many approaches to measuring environmental impact but that there was not a consistent or universally accepted metric or process. To bridge this gap, a scoring system was developed for the entire mine to market lifecycle. For each lifecycle stage, a set of goals and indicators were proposed against which to rate sustainability. The goals and indicators are tailored here for metal mining and reproduced in Table 1. The proposed indicators only

include the core activities that are seen as moderately to extremely important to most (base and precious metals) mining operations. A mine site may find it necessary to modify the criteria by adding or dropping goals and indicators to better represent their specific situation.

Kogel's relative ranking approach will be used later to determine the extent to which the technological contributions to improved design, operation and management of surface mine haulage roads could play a role in SD.

Energy Consumption – Surface Mine Haulage

Since many of the indicators in Table 1 implicate energy in one or other form – either as raw materials or resources, GHG emissions and energy consumption, a preliminary analysis of energy consumed in mining will enable the capacity of surface mine haulage to contribute to SD improvements to be gauged. Table 2 summarises energy, water and GHG emissions following Mudd (2008), reported per kilogram of gold produced, from both surface open-pit and underground sources (averaged over grade).

Table 2 tends to reflect the higher energy-intensity of underground, as compared with open-pit mining operations. In addition, the potential SD targets are different from surface mining, by virtue of the differing systems requirements in both cases. When considering surface mining energy requirements alone, by modifying the Energy and Environmental Profile of the US Department of Energy (2002), the relative energy requirements for mine haulage-related activities in a 5mtpa surface gold mine can be assessed, as shown in Table 3.

Figure 1 depicts the role of mine haulage in terms of total energy consumption and, by implication, where the greatest benefits lie when increasing the efficient use of natural (energy) resources required to supplement the mining process. Improved efficiency in the use of these resources is beneficial for both the mine, through enhanced capability for production, and the community in which they operate, through preservation of non-renewable resources.

LINKING IMPROVED HAUL ROAD DESIGN TO SD TARGETS

Most mine operators will agree that a strong relationship exists between well constructed and maintained roads and safe, efficient mining operations. What is perhaps less well documented are the environmental contributions that technology in road design and management can deliver to SD reporting, in the short and long-term. Utilising innovation is the key to long-term sustainability and as a means of positioning the industry for the imminent structural changes to the economy and environment, changes which are now within the operating life of many mines, haul roads and haul trucks.

Large modern surface mining operations generally incorporate high standards of road design work into the overall mine plan. The result is usually a well constructed roadway that is safe and efficient to operate and easy to maintain. This situation can be quite different for smaller surface mining operations where either only a few vehicles are used in the transport of material or traffic volumes are comparatively low. Larger operations usually exhibit a stronger and more well-defined management philosophy in which special consideration is often given to haul road design, management and maintenance, whereas smaller

operations, by virtue of their size, generally operate without such extensive design and management input (MHSC, 2009 and Randolph and Bolt, 1996).

One of the first, and arguably most important initiatives to formalize the approach to design and management of mine haul roads was the USBM Information Circular 8758 - Design of Surface Mine Haulage Roads - A Manual, by Kaufman and Ault (USBM, 1977). The aim of this publication was to provide a complete manual of recommended practices that promote safer, more efficient haulage. The authors recognized that the development of surface mine haulage equipment had outstripped available (mine) road design technology, resulting in numerous accidents caused by road conditions that were beyond the vehicle's and driver's ability to negotiate safely.

The content of the USBM design guidelines was developed primarily in response to haulage accidents, but also included current practice information from mining companies and equipment manufacturers. Content covered such aspects as road alignment (both vertical and horizontal), road cross-section, construction materials, surfacing materials, road width, cross-slope and berm design, together with traffic control and drainage provisions, as was suggested criteria for road and vehicle maintenance and for runaway vehicle safety provisions. At the time of its publication, the USBM guidelines did not explicitly address SD target contributions, but rather did so implicitly through consideration of resource (energy) utilisation enhancements.

A more rigorous approach categorizes the various issues that must be addressed in a haul road design (following Thompson and Visser, 1999);

- The geometric design - commonly the starting point for any haul road design and refers to the layout and alignment of the road, in both the horizontal and vertical plane, 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, 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 structural design provides haul road 'strength' to 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 – most often soft, weak or wet in-situ materials below the road surface.
- The functional design, centred on the selection of wearing course (or sheeting) materials where the most suitable choice and application is required which minimizes the rate of defect (rolling resistance) formation in the road surface, which would otherwise compromise road safety, performance and efficiency.
- The maintenance design which identifies the optimal frequency of maintenance (routine grading) for each section of haul road in a network, thus maintenance can be planned, scheduled and prioritized for optimal road performance and minimum total (vehicle operating and road maintenance) costs,

and thus maximising resource efficiency across the network. This is especially important where road maintenance assets are scarce and need to be used to best effect.

One of the greatest challenges to recognizing opportunities for improvement in operations is that the focus is typically on one component of a greater system (Watson, 2008). Conflicting issues arise when typically individual elements of a haulage system are considered in isolation, not as a whole. Concepts such as resource and energy efficiency, water consumption, GHG emissions and safety and health in haulage operations cannot be addressed in isolation. Designing a safe and efficient haul road is best 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 and safety is often compromised. This will most often be seen as inherently 'unsafe', 'maintenance intensive' and commonly, high rolling resistance –high operating cost roads. This combination of circumstances would not translate well on any SD indicator score-card.

The cure, however, is not necessarily just 'more frequent maintenance'; 'newer trucks', 'better driving habits', etc. No amount of ad-hoc remediation will 'fix' a poorly-designed road to deliver SD indicator improvements. Each component of the road infrastructure must be correctly addressed at the design stage. Figure 2 illustrates the integrated design approach. The design goal of minimising total road-user costs fits well with the challenge of providing realistic, long-term sustainability solutions that can be developed and implemented in the short-term. Using the integrated design approach outlined above, together with Kogel's ranking of SD goals, enables the specific contributions of each haul road design component to be linked with its SD target, as shown in Table 4.

As has been shown above, with truck-based hauling systems, the design and management of the mine haul road network is a critical and vital component of both production process and the longer-term aim of meeting SD targets. As such, under-performance of a haul road will impact immediately on mine productivity, costs and SD indicators. Central to the cost of truck hauling is the concept of rolling resistance (expressed here as a percentage of Gross Vehicle Mass (GVM)). Taking an electric-drive rear-dump ultra-truck of 376t (GVM) as an example, on a ramp road with a basic rolling resistance of 2%, an additional 1% rolling resistance will reduce energy efficiency by 10-13%, whilst on a flat surface road, energy efficiency will reduce by between 18-26%.

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

Geometric Design

The geometric layout of a mine haul road is dictated to a great extent by the mining method used and the geometry of both the mining area and the orebody. Mine planning software enables various haul road geometric options to be considered and the optimal layout selected, both from a road design and economic (lowest cost of provision) perspective (MineMap, 2007). Whilst these techniques often have default design values embedded in the software, it is nevertheless necessary to review the basic concepts of geometric design if any modifications are to be considered in the design of mine roads, either on the basis of economics or, more critically, from a safety perspective.

The road layout – or alignment, both horizontally and vertically is generally the starting point of the geometric design. Practically, it is often necessary to compromise between an ideal layout and what mining geometry and economics will allow. Any departure from the ideal specifications will result in reductions of both road and transport equipment performance.

Broadly speaking, safety and good engineering practice require haul road alignment to be designed to suit all vehicle types using the road, operating within the safe performance envelope of the vehicle, or, where this is not possible, at the speed limit applied. Ideally, geometric layout should allow the vehicles to operate at their maximum safe speed, but since the same road is used for laden and unladen haulage, there is often the need to minimize laden travel times, through appropriate geometric alignment, whilst accepting compromise (generally in the form of speed limits) on the unladen return haul.

The process of geometric design begins with a simple plan, and this plan is improved incrementally as the specifications are met. 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 (Vagaja and Thompson, in press) address;

- Vertical alignment issues:
 - Stopping distance limits of truck;
 - Sight distances;
 - Overtaking and safe following distances.
- Horizontal (longitudinal) alignment issues:
 - Width of road;
 - Curvature and switchbacks;
 - Curve super-elevation (banking);
 - Run-out;
 - Cross-slope or camber;
 - Intersection layout;
- Combined alignment

- Safety berms
- Drainage design
- Roadside furniture
- Safe systems – vehicle, operator, speed and road

Haul Road Structural Design

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

Vertical compressive strains induced in a road by heavy wheel loads decrease with increasing depth which permits the use of a gradation of materials and preparation techniques; stronger materials being used in the upper regions of the pavement. The road as a whole must limit the strains in the sub-grade (in-situ) to an acceptable level and the upper layers must in a similar manner protect the layers below. Using this premise, the road structure should theoretically provide adequate service over its design life.

In general terms, applied load, sub-grade strength and the pavement structural thickness and layer strength factors predominantly control the structural performance of a haul road. An upper limit of 2000 microstrain is generally placed on layer strain values. Strain values exceeding 2500 microstrains are associated with unacceptable structural performance in all but the most lightly traffic and short-term roads.

Figure 3 shows the results of a typical design exercise, showing how a poor structural design (LHS section) is associated with excessive vertical strain – especially in the soft in-situ material – which leads to deformation of this layer. When this occurs, no amount of surface maintenance will cure the problem, it will be necessary to either replace the in-situ with selected compacted fill or to increase the base layer thickness above in-situ.

Haul Road Functionality and Deterioration

Equally important as the structural strength of the design, is the functional trafficability of the haul road. This is dictated to a large degree through the selection, application and maintenance of the wearing course (or road sheeting) materials. Poor functional performance is manifest as poor ride quality, excessive dust, increased tyre wear and damage and an accompanying loss of productivity. The result of these effects is seen as an increase in overall vehicle operating and maintenance costs and a reduction in energy efficiency.

The functional design of a haul road is the process of selecting the most appropriate wearing course material or mix of materials, typically natural gravel or crushed stone and gravel mixtures that are commensurate with safety, operational, environmental and economic considerations. Typical specifications for wearing course material selection are illustrated in Figure 4 after Thompson and Visser (2006). The selection range 1-2 was derived according to mine road-user requirements which in turn minimises (but does not totally eliminate) excessive rolling resistance (>2%) progression rates. 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 5.

Haul road dust palliation

Dust generation is the process by which fine wearing course material becomes airborne. The amount of dust that will be emitted is a function of the wind-erodibility of the material involved and the erosivity of the actions to which the material is subjected. In broad terms, the effectiveness of any dust suppression system is dependant on changing material wind-erodibility or erosivity. A high proportion of wearing course silt and fine sand fractions (i.e. 2-75 μ m) is an indicator of excessive erodibility.

The motivation for the use of some additional agent to reduce a material's inherent erodibility is based on increasing particle binding. The finer fraction, although contributing to cohesiveness, also generates much of the dust, particularly when the material is dry. The presence of larger fractions in the material will help reduce erodibility of the finer fractions, as will the presence of moisture, but only at the interface between the surface and the mechanical eroding action. This forms the basis of the water-based dust suppression techniques used most commonly on mine haul roads.

When chemical-based dust suppressants are applied to an appropriate wearing course, the average degree of dust palliation and the period over which it applied often seen to be considerably better than that achievable by water-based spraying alone (Thompson and Visser, 2002). However, in terms of cost-effectiveness, an evaluation is required with which to determine the extent of the cost benefits attributable to chemical-based dust suppression, together with an indication of those factors likely to alter the trade-off between water- and chemical-based dust palliation. A typical approach is illustrated in Figure 5.

Maintenance Management

Design and construction costs for the majority of haul roads represent only a small proportion of the total operating and road maintenance costs and in particular, the use of an appropriate road maintenance management strategy has the potential to generate significant improvements to many SD targets – particularly in the light of increases in rolling resistance due to the interactive effects of traffic volume and wearing course deterioration (Thompson and Visser, 2003).

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. A maintenance management system (MMS) for mine haul roads is briefly described here, following Thompson and Visser (2006) to address these needs.

Maintenance management systems

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, the agency maintaining the haul road network is directly affected by road-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 rolling resistance. The selection of a maintenance program 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 6.

Mine haul road maintenance intervals are 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 road maintenance resources to provide the greatest overall benefit. This optimization approach is inherent in the structure of a maintenance management system (MMS) for mine haul roads.

CONCLUSIONS

Haul road design and management forms a principal component of the transport operation in surface mines. Transportation of both the mineral product and associated waste is, in itself, a significant cost item in terms of total cost of production. Truck haulage costs can account for up to 50% of the total operating costs incurred by a deep open-pit operation and any savings generated from improved road design and operation have benefits that extend well-beyond company profitability, into the broader issues of SD. A typical surface metal-mining operation can ascribe over 70% of its energy consumption to haulage operations, of which the majority is linked to haul truck fuel consumption,

Many SD reporting strategies encompass energy efficiency, water consumption, GHG emissions and safety innovation amongst the key measures of performance improvement. It is in these areas that improvements in haulage system design and management can contribute positively to long-term sustainability solutions, in a relatively short-term implementation timeframe. Short-term value can clearly be derived from reduced energy, water and safety-incidents associated with mine haulage, whilst any costs associated with GHG emissions levied in the future also leverage longer-term benefits.

From a road design perspective, the design goal of minimising total road-user costs fits well with the challenge of providing realistic, long-term sustainability solutions that can be developed and implemented in the short-term. Using an integrated road design approach, covering geometric, structural, functional and maintenance design, together a ranking of SD goals, the specific contributions of each haul road design

component can be linked to a specific SD target. This serves as a basis for evaluating the economic and environmental contributions that technology in road design and management can deliver to sustainable operations. Utilising innovation is the key to long-term sustainability and as a means of positioning the industry for the imminent structural changes to the economy and environment, changes which are now within the operating life of many mines, haul roads and haul trucks.

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FIGURE CAPTIONS

Fig 1 - Haulage energy consumption in a 5mtpa surface gold mining operation (after US Department of Energy (2002) data).

Fig 2 - Typical integrated approach to mine haul road design

Fig 3 - Comparison of poor (LHS) and good (RHS) structural designs

Fig 4 - Recommended wearing course material selection ranges for mine haul roads

Fig 5 - Basis of dust palliative cost-benefit evaluation

Fig 6 - Minimum total cost solution and required road maintenance frequency from vehicle operating costs and road maintenance cost considerations

TABLE CAPTIONS

Table 1 Relative ranking of SD goals for metal mining (modified after Kogel, 2009)

Table 2 Average environmental costs for gold production (from open-pit and underground sources) per kilogram metal produced (after Mudd, 2008).

Table 3 Mine haulage energy requirements for a 5mtpa surface gold mining operation

Table 4 Linking haul road design components with relative ranking of SD goals for metal mining.

Table 5 Recommended parameter ranges for mine haul road wearing course material selection

FIGURES

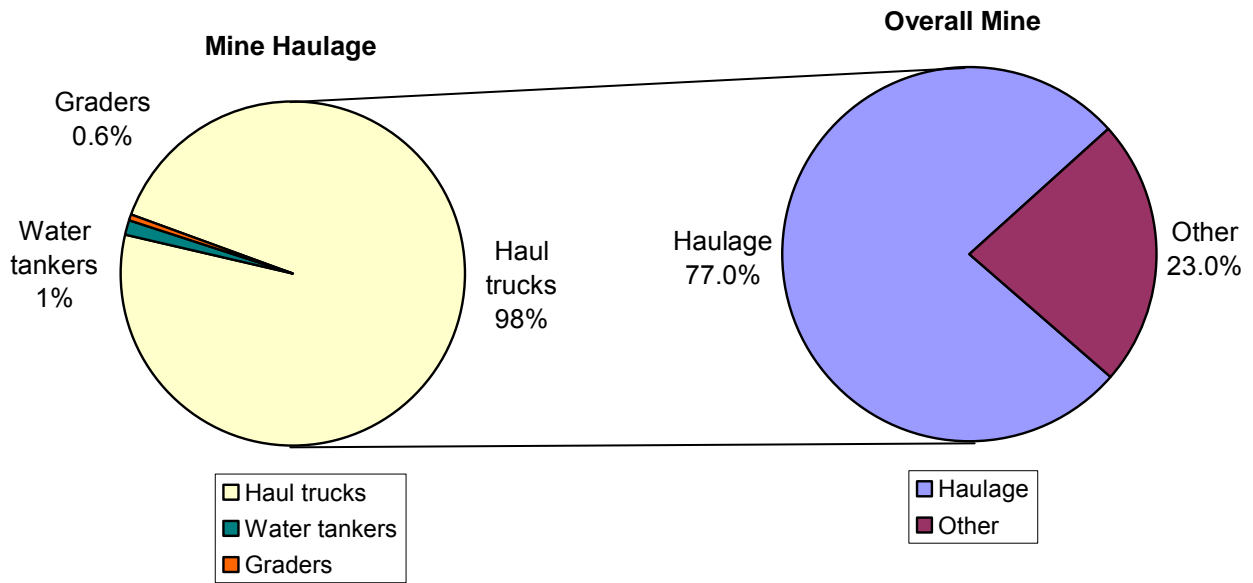


Fig 1 - Haulage energy consumption in a 5mtpa surface gold mining operation (after US Department of Energy (2002) data).

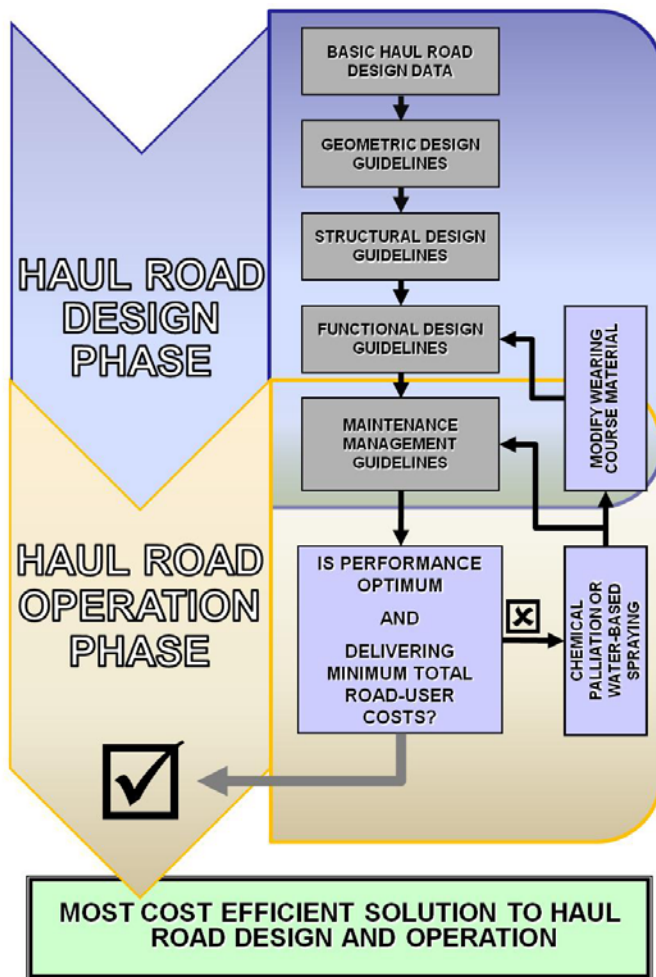
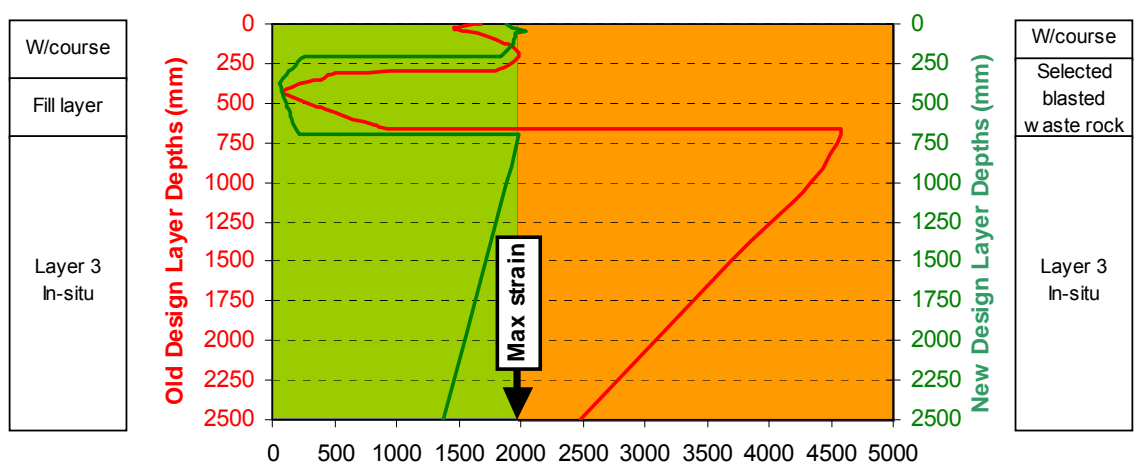


Fig 2 - Typical integrated approach to mine haul road design

Structural design comparisons



Vertical (micro) strain in pavement

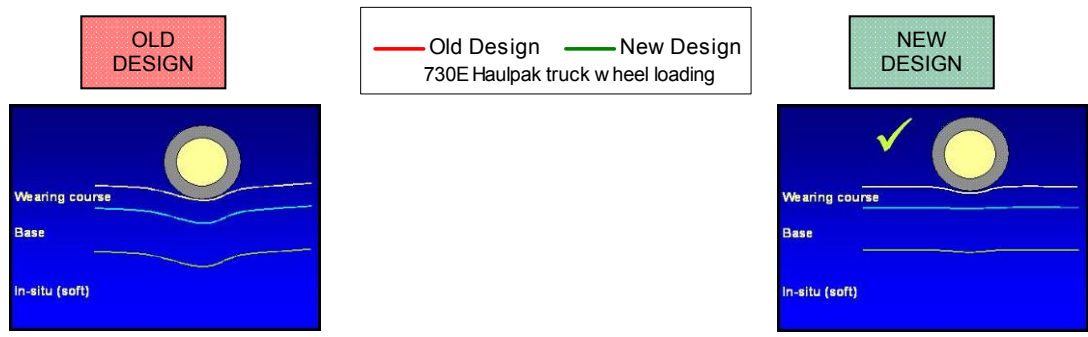
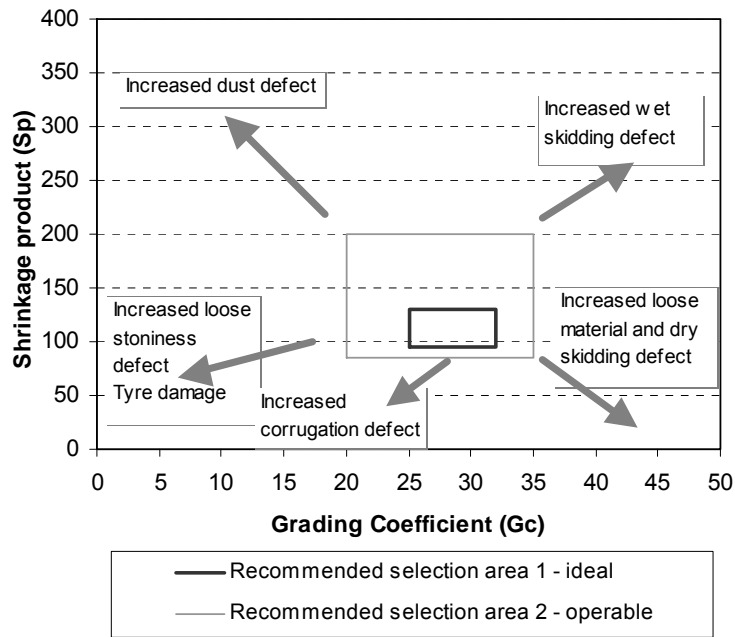


Fig 3 - Comparison of poor (LHS) and good (RHS) structural designs



$$Sp = LS \times P425$$

$$Gc = \frac{(P265 - P2) \times P475}{100}$$

where;

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

Fig 4 - Recommended wearing course material selection ranges for mine haul roads

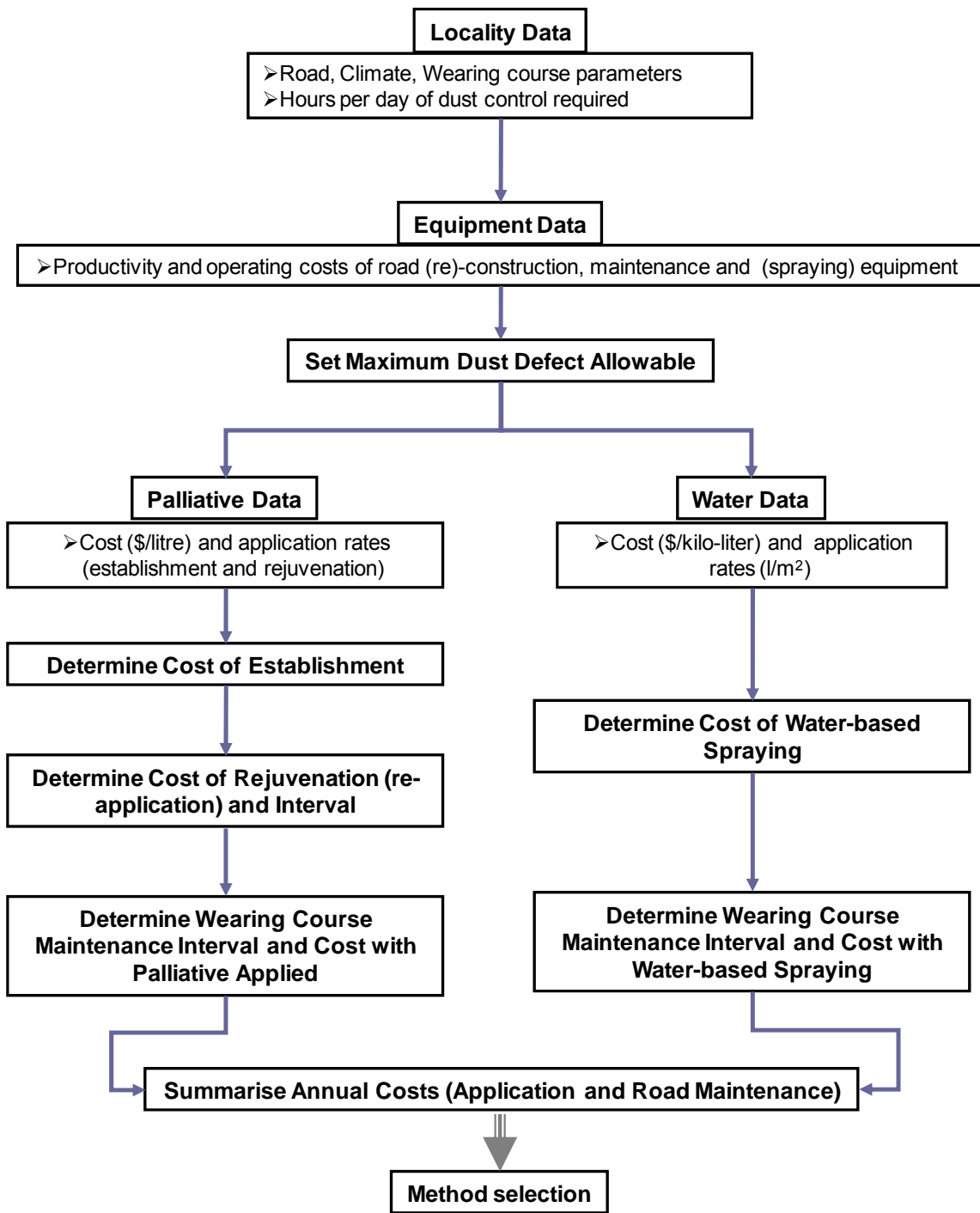


Fig 5 - Basis of dust palliative cost-benefit evaluation

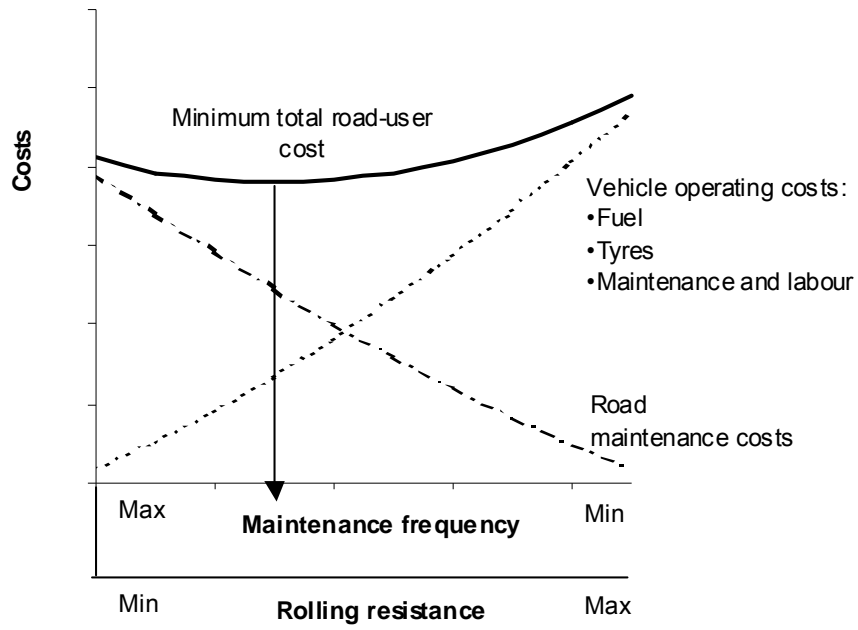


Fig 6 - Minimum total cost solution and required road maintenance frequency from vehicle operating costs and road maintenance cost considerations

TABLES

Table 1 Relative ranking of SD goals for metal mining (modified after Kogel, 2009)

Goal	Indicator
Increase process recovery	2
Manage water effectively	1
Mine safely and statutory compliance	1
Recyclable/reusable	1
Reduce CO _{2-e} emissions	1
Reduce energy consumption	2
Reduce H ₂ O consumption	1
Reduce mining footprint	1
Reduce raw material consumption	1
Restore habitat post mining	1
Utilise waste heat	U/G mostly
Key: Extremely important (1) Moderately important (2)	

Table 2 Average environmental costs for gold production (from open-pit and underground sources) per kilogram metal produced (after Mudd, 2008).

Energy Consumption	Water Consumption	Greenhouse Emissions
143 GJ	691,000 Litres	11.5 t CO _{2-e}

Table 3 Mine haulage energy requirements for a 5mtpa surface gold mining operation

Equipment	Units	All units (MJ/kg gold)
Haul truck	38	51 660
Water tanker	2	647
Grader	2	53
Total haulage		52 360
TOTAL MINE		68 044
<p>Note: 20-year life of mine, 5.90 g/tonne grade, 5mtpa ore, strip ratio 9.65 tonne/tonne. Average depth of operations 475m.</p>		

Table 4 Linking haul road design components with relative ranking of SD goals for metal mining.

SD Goal	Road Design Component Implicated			
	Geometric	Structural	Functional	Maintenance
Increase process recovery	Not applicable			
Manage water effectively			1	1
Mine safely and statutory compliance	2		2	
Recyclable/reusable	3	3	3	3
Reduce CO _{2-e} emissions	4		4	4
Reduce energy consumption	5		5	5
Reduce H ₂ O consumption			6	6
Reduce mining footprint	7			
Reduce raw material consumption	8		8	8
Restore habitat post mining		9	9	
Utilise waste heat	Not applicable			
Notes				
1	Functional design – reduction or elimination of dust generation from wearing course materials and maintenance design – reduced blading intervals			
2	Primarily geometric and functional design issues, following MHSC (2009) and USBM (1981).			
3	Indirectly, through increased asset utilisation and equipment and road `operating life arising from improved road performance			
4	Optimised geometric design maximising engine clean-burn, reduced idle time and stop/start manoeuvring			
5	Reduced road rolling resistance leading to reduced engine fuel consumption per tonne hauled.			
6	As (1) above – note that water for dust allaying need not utilise pristine water.			
7	Optimising geometric design to reduce road widths in conjunction with computerised asset management and location systems and possibly steeper ramp grades			
8	As (5) above – specific to energy consumption. Also associated with tyre consumption and equipment operating life			

9 Reducing damage to natural in-situ materials through tailored structural design using local (mine) materials, reduced fugitive dust emissions, reduced watering run-off.

Table 5 Recommended parameter ranges for mine haul road wearing course material selection

Impact on Functionality Below Recommended Range	Material Parameter	Range		Impact on Functionality Above Recommended Range
		Min	Max	
Reduce slipperiness but prone to raveling and corrugation	Shrinkage Product	85	200	Increased dustiness and poor wet skid resistance
Increased loose stones, corrugations and potential tire damage	Grading Coefficient	20	35	Increased raveling and poor dry skid resistance
Reduced dustiness but loose material will ravel	Dust Ratio	0,4	0,6	Increased dust generation
Increased loose stoniness	Liquid Limit (%)	17	24	Prone to dustiness, reduced raveling
Increased loose stoniness	Plastic Limit (%)	12	17	Prone to dustiness, reduced raveling
Increased tendency to ravel, loose stoniness	Plasticity Index	4	8	Prone to dustiness and poor wet skid resistance
Poor wet weather trafficability, churning, excessive deformation and cross-erosion. Maintenance intensive	Soaked CBR at 98% AS 1289 6.1.1	80		Increased resistance to erosion, rutting and improved trafficability
Ease of maintenance, vehicle friendly ride and no tyre damage	Maximum Particle Size (mm)		40	Poor surface finish following maintenance, potholing and potential tyre damage