MINE HAUL ROAD DESIGN AND MANAGEMENT: A CURRENT PRACTICE REVIEW

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Abstract

Well designed and maintained haul roads are the key to minimizing truck haulage on-road hazards and costs, as well as increasing productivity. In practice however, designing and managing a haul road for optimal performance is often difficult to achieve, especially when resources assigned to design and construction are constrained. By understanding how a road design is developed from geometric, structural, functional and maintenance considerations, and critically, the interplay between these components in design and operation, optimal performance can be achieved.

This paper briefly summarizes the evolution of mine haul road design, from the seminal USBM work of Kaufman and Ault in 1977, through to current geometric, structural, functional and maintenance management design components. These augmented design and management guidelines have been developed over the past decade, both in response to the requirements of mine operators for safer and more efficient haulage systems, the truck manufacturers' requirements for a more predictable and controlled operating environment and the recognition of human factors as a significant contributor to haulage accidents. Whilst the human factor is the most problematic to address in a road design, the paper shows the more that is known about human error, the better a road can be designed to accommodate those actions or non-standard practices that would, on a poorly designed road, invariably escalate an error into an accident**.**

Introduction

The haul road design and subsequent road management and maintenance forms a principal component of a transport operation in surface mines. Most mine operators will agree that a strong relationship exists between well constructed and maintained roads and safe, efficient mining operations. 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 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 engineering methodologies are used for haul road design, management and maintenance, whereas smaller operations, by virtue of their size, generally operate without such extensive design and management input (Fourie et al; 1998, Randolph and Bolt; 1996). Where design and management input is lacking, an empirical design approach based on local experience may eventually result in safe, economically optimal roads but the learning curve is shallow and slow. This approach does not lend itself to an understanding of the deficiencies in the road design process and more importantly, when haul road safety is sub-standard, the empirical approach does not easily allow the unsafe condition nor the road design deficiency implicated in an accident to be identified.

One of the first, and arguably most important initiatives to formalize the approach to design and management of mine haul roads was the USBM (1977) Information Circular 8758 - Design of Surface Mine Haulage Roads - A Manual, by Walter Kaufman and James Ault. 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 well as suggested criteria for road and vehicle maintenance and for runaway vehicle safety provisions.

Adopting and categorising this content according to a set of integrated road design components (following Thompson and Visser; 1999) that should be addressed in a haul road design, gives four broad design components to consider;

- 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 it 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 centres on the selection of wearing course (or surfacing) materials where the most suitable choice and application is required which minimizes the rate of defect formation in the road surface, which would otherwise compromise road safety and performance. The functional design is not a significant contributor to haul road structural strength.

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

Comparing the content of the USBM work to the more recent 'integrated mine road design' methodology of Thompson and Visser (1999), it is evident that the USBM work addressed each of the design components and the associated engineering methodolgy, although not specifically relating each design guideline to its associated design component. 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 often manifest as inherently unsafe, maintenance intensive and high rolling resistance roads. This combination of circumstances translates into hazardous, high-operating cost, low-productivity haul roads. The cure, however, is not simply to increase routine (blading/scraping) road maintenance frequency, nor through improved driving training, etc. Without recourse to road re-design and rehabilitation (complete overhaul), no amount of routine maintenance will fix a poorly-designed road. Preferably, components of the road infrastructure design process must be correctly addressed and integrated with each other at the design stage, as illustrated in Fig. 1.

Safety Critical Defects In Mine Road Design

Just as when developing the original USBM guidelines in 1977, amending existing or developing new mine road design methodologies requires reference to current surface (powered) haulage accident and incident records to identify the major contributory factors that led to these accidents. Several studies have been undertaken, both in the United States (Randolph and Boldt; 1996, USBM; 1981, Aldinger et al; 1995), and South Africa (Fourie et al; 1998). From an analysis of the principal sub-standard surface mine road design factors which were most frequently encountered in the

accident reports, these studies lead to the identification of several key problem areas which should guide development of appropriate design recommendations.

Based on the MSHA data compiled from Jan. through Dec. 2008, the 'Powered Haulage – Haulage Trucks' class of accidents accounted for 8.2% of accidents both at surface coal (80) and metal (56) mines, 4.1% (6) at non-metal surface mines, 3.4% (36) at surface stone operations and 3.2% (27) at sand and gravel operations . Whilst this data puts the paper into context, without referring to each incident report to examine the details of the accident, it is difficult to determine how the role of road design impacts on safety. A more detailed textual analysis was reported by Randolph and Boldt (1996), based on the analysis of Aldinger et al (1995), using accident reports over the period 1989-1991, which is shown in Fig.2.

In their study of surface coal mining, equipment operation was the most common category of accident for haulage trucks (46% or 1251 accidents). Within the equipment operation sub-set, jarring (38%) and loss of control (27%) accidents predominate. Of the jarring sub-set, rough ground (45%), loading (34%), and dumping (15%) were the main root-cause factors. Loss of control sub-set included too close to edge (36%) and runaway (28%). Whilst there is no specific reference to the design component that was implicated in these accidents, it has been shown that haul road structural design defects contribute significantly to jarring-rough ground incidents (Miller et al; 2004), whilst functional and geometric design were likely contributory factors in the loss of control accidents.

The MHSA safety bulletin (Fesak, Breland and Spadaro; 1996) reported the results of 4397 accidents from 1990-1996 from which some 1300 lost time accidents associated with water trucks, front end-loaders, tractor/scrapers, ore carrier/large trucks, ore haulage trucks, or other utility trucks were isolated and evaluated. They reported that 49% (640) lost-time accidents (of which 96 were fatal) were associated with roads and (traffic) control issues. However, the specific road or

(traffic) control design component that was deficient or implicated as an accident root-cause was not evaluated.

Internationally, a study conducted in South Africa by Fourie et al (1998) found that in the majority of accident reports analyzed, scant attention or recognition was given to basic road design components, even where the deficient condition which led directly to the accident was clearly stated. Figure 3 shows how the engineering methodology of design relates to attributable accident rate (accidents that involved vehicles on mine haul- or road-ways). As the formality of the design methodology increases, the attributable accident rate decreases. In this context, formality of design is defined as;

- Formal design methods; Site-and location-specific geometric, structural, functional and maintenance designs tailored to operating conditions and subject to engineering review and revision.
- Informal design methods; Company-wide generic design guidelines not tailored to individual mine operating conditions nor subject to regular revision.
- No design methods; Informal un-documented approach to provision of mine roads, no standard working methods, materials or equipment.

Using the South African attributable accident database, a further analysis was conducted to determine the sub-standard act or condition which either led to, or was implicated in each attributable accident. The principal deficient road design factors thus determined were;

- Geometric Design
  - Junction layout:
    Poor junction layout or incorrect or inappropriate signage. Poor visibility of or from junction. Non uniformity of traffic controls.

- o Safety berms:

  No safety berms where road runs on an embankment (fill area) or berms too small. No berm maintenance. Vehicles which lost control on these sections ran off the road.

- o Road shoulders:

  Collisions with vehicles (breakdown, etc.) parked on roadside, no shoulder or road too narrow. Poor demarcation of parked equipment. Poor or temporarily obstructed sight lines.

- o Run-aways- brakes:

  Accidents due to brake failures whilst hauling laden down-grade or vehicle run-aways down-grade. Steep gradients and operator inability to handle those grades (speed/retarder management).

- Structural Design

  - o Jarring:

    Poor ride quality due to permanent deformation in base or in-situ materials and reflected damage in surfacing (wearing course).

  - o Directional stability:

    Large areas of potholing and slip cracks. Evasive action of vehicle in leaving demarcated lane.

- Functional Design

  (May also be in part attributable to maintenance design issues where poorly selected wearing course material is not remediated by increased routine road maintenance activity).

  - o Dustiness:

    Wearing course material selection inappropriate.

  - o Poor visibility:

Excessive dustiness generated from vehicle wind shear or due to windy conditions, especially at night.

- o Skid resistance:

Wet wearing course material, either after rain or watering to allay dust. In several instances, dry skid resistance also problematic. Inappropriate material for geographic location of road and/or inappropriate speed.

- o Large stones:

Haul trucks and utility vehicles running over large stones protruding from the wearing course. Spillage from trucks is also a common causative factor. Evasive action of vehicle in leaving demarcated lane.

The percentages of agency factors implicated in South African attributable accidents are presented in Fig.4. Of the total transport accidents analyzed and categorized, 47% could be directly attributed to road design and operation. 60% of these were related to non-standard acts (practices and other) and human error. Of the 40% associated with sub-standard road design factors, geometric and functional components predominate as the agencies implicated, with maintenance and structural design exhibiting less influence.

Solutions to mine haul road safety problems predominantly relate to the road design components of geometry and function, and to a lesser extent, structure and maintenance. However, this work has shown that human factors (including non-standard practices), vehicle (mechanical) factors and other deficiencies are all implicated in attributable accidents. Figure 5 illustrates the relative percentage contributions of each of these factors to attributable accidents.

Whilst improved mine haul road design activities may well reduce design-related accidents, it would appear that little recognition is given to the human factors which are a significant contributor

to haulage accidents. Fig. 5 illustrates that 25 percent of accidents in which human error was implicated, were also associated with deficiencies in the road design itself. In other words, the road design did not contribute to potential recovery from human error but instead escalated an error into an accident.

The human factor is the most problematic to address in road design. Ideally, a road should be designed to be more forgiving of human error, preventing an accident or reducing the severity of its consequences. In this way a haul road can be designed to compensate for human error; the more that is known about human error, the better the road can be designed to accommodate those actions or non-standard practices. This premise forms the basis of road safety design audits used on public roads (AUSTROADS; 1994).

Mine Road Design Guideline Development

Just as the authors of the original USBM guidelines recognized that the development of surface mine haulage equipment had outstripped mine road design technology, the continuing increase in truck size to-date, together with more recent powered haulage accident and incident analyses, has warranted further development of mine road design guidelines. Using the USBM (1977) manual as a starting point, these key developments are summarized below, as applied to the geometric, structural and functional design components defined earlier.

Geometric Design

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

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

The USBM data of Kaufman and Ault still forms a sound basis for this design component – albeit with updates to truck types and dimensions. 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. Some of the more common geometric design problems are listed below;

- Avoid sharp horizontal curves at or near the top of a grade section of road. If a horizontal curve is necessary, start it well in advance of the vertical curve.

- Avoid switchbacks where possible - but if mine plan dictates their use, make radius as large as possible and avoid placing on grade.

- Avoid sharp horizontal curves requiring a (further) speed reduction following a long sustained downgrade where haul trucks are normally at their highest speed.

- Avoid short tangents and varying grades, especially on multi-lane roads. Grades should be smooth and of consistent grade percentages.

- 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.

- Avoid stopping and starting a laden haul truck on grade.

- Avoid intersections with poor drainage. Drainage design at intersections should stop any ponding of water against intersection super-elevated curves.

- 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.

- Preference should be given to 3-way over 4-way intersections. Avoid staggered or other multiple road junctions. Always provide splitter or median islands to prevent vehicles cutting corners through a junction.

- Avoid signage, vegetation, roadside furnishings or excessively high splitter islands that would otherwise eventually limit sight distances in any of the four quadrants required.

- Avoid having the inside (and lower) side of a super-elevated bench-to-ramp access road at a steeper gradient than the ramp road itself; the inside grade of the curve should not exceed that of the ramp road.

With regards to safety berms, crest (outslope) or road-edge (windrow) berms 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 material comprising the berm and it's natural angle of repose significantly influence how the berm performs. The slope of the sides of the safety berm should be preferably as steep as possible – 1.5H:1V - this ensures better re-direction of the truck and less tendency to climb and topple. But in doing this, stability and maintenance of height must be assured, since a flat or low berm can also cause truck roll-over. For large haul trucks, the berm height should be at least 66% of the truck wheel diameter.

Truck GVW and approach angle has a significant deformation effect on the berm, which is typically constructed from unconsolidated material. The ability of a berm to re-direct reduces as

angle of approach increases. Furthermore, large tire sizes and non-centering steering mechanisms reduce the tendency of the truck to redirect itself when encountering a berm. With 4x6 and 6x6 wheel drive articulated dump trucks, berm dimensions in excess of 66% wheel diameter are recommended, due to the truck's ability to climb smaller berms. Other factors such as inertial characteristics, sprung mass ratio and suspension characteristics indicate significantly different response patterns for haul vehicles when encountering berms.

Structural Design Guidelines

The California Bearing Ratio (CBR) cover-curve design method (USBM; 1977) has been widely applied to the design of mine haul roads in which untreated materials are used and is based on the CBR penetration test. The CBR of a material is expressed as a percentage of the penetration resistance of that material compared to that of a standard value for crushed stone. The value is normally derived from laboratory tests, although field impact and penetration testing also delivers indirect CBR values. In all but arid and semi-arid environments, the CBR value adopted in the design should be based on a soaked CBR test. In this design procedure, pavement cover thickness above a material with a particular CBR is determined as a function of applied wheel load and the CBR of the material. The same technique can be used for successive layers – the only requirement being that successive layers must be of higher CBR than the preceding layer.

Although the CBR cover-curve approach has generally been superseded by the mechanistic approach described later, there are some design cases where it would still be appropriate. In Fig. 6, an updated version of the USBM CBR design charts are presented (after Thompson, 2010), appropriate for the wheel loads generated by typical 6-wheeled rear-dump trucks, together with the approximate bearing capacities of various soils types defined by the Unified Soil Classification (USCS, following Test Designation D-2487 of the American Society for Testing and Materials (ASTM); 1998)

and the American Association of State Highway and Transportation Officials' (AASHTO; 1982)

systems.

Eq. (1), following Thompson (2010a), can alternatively be used to estimate the thickness of cover

(Z_{CBR} (m)) required above a material of California Bearing Ratio (CBR %);

$$Z_{CBR} = \frac{9.81t_w}{P} \left[0.104 + 0.331e^{(-0.0287t_w)} \right] \left[2x10^{-5\left(\frac{CBR}{P}\right)} \right] \left[\left(\frac{CBR}{P}\right)^{-\left(0.415 + Px10^{-4}\right)} \right] \tag{1}$$

Where t_w is the truck wheel load (metric tons), P is tire pressure (kPa) and CBR is the California

Bearing ration of the material (%). To replicate the increased stresses generated by a rear dual-

wheel axle which occur deeper in a road layer, the concept of Equivalent Single Wheel Load (ESWL)

can be used to estimate the cover Z_{ESWL} (m) required using Eq. 2 (following Thompson; 2010a) as;

$$Z_{ESWL} = Z_{CBR} + \left[0.184 + \left(0.086CBR + \frac{17.76CBR}{t_w} \right) \right]^{-1} \tag{2}$$

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

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.

When a mechanistic design approach is used to determine the response of the road to an

applied load, a multi-layered elastic model is developed representing the various haul road layers in

the design (Thompson and Visser, 1996). Software is available which can be used to solve multi-

layer problems in road design, including ELSYM5A (FHWA, 1985) and CIRCLY (MinCad, 2008).

Irrespective of the solution software used, the approach is similar. The effective elastic (reslilient)

modulus of (E_{eff}) and Poisson's ratio (μ, typically 0.35) define the layerworks material properties required for computing the vertical strains (ε_v) in the road. In addition to the material properties, a layer thickness (generally 200mm) is also specified for the wearing course. By varying the thickness of the base-layer, a solution for maximum strain in any pavement layer that is below the limiting strain criteria for that class of road is found. Generally, a three layer model is sufficient where the road is built directly on sub-grade fill or in-situ. If the construction incorporates ripped and compacted in-situ, this may also be added as an additional layer. For computational purposes, the layers are assumed to extend infinitely in the horizontal direction.

The applied load is calculated according to the mass of the vehicle and the rear dual wheel axle load distributions, from which the single wheel load is found. The load application is determined from dual wheel geometry and together with tire pressure, the contact stress is calculated. Fig. 7 summarizes the layered elastic model and data requirements. The strains induced in a road are a function of the effective elastic (resilient) modulus (E_{eff}) values assigned to each layer in the structure. Fig. 6 gives recommended modulus value correlations to USCS and AASHTO classification systems. To select suitable modulus values for in-situ materials, the associated range of CBR values are also given. Other values are published by Thompson and Visser (1996) and AUSTROADS (2009) from where Eq. (3) is taken, which, when used in conjunction with layer CBR values, determines the modulus values (E_{eff}, MPa). In each case however, care should be taken to ensure that the general correlations presented here are consistent with soil properties not directly assessed in the derivation of the equation.

$$E_{eff} \quad = \quad 17.63 CBR^{0.64} \tag{3}$$

The mechanistic design methodology is presented by Thompson and Visser (1996). In general terms, applied load, sub-grade strength and the pavement structural thickness and layer resilient modulus predominantly controls the structural performance of a haul road. An upper limit of 2000 microstrain is generally placed on layer vertical compressive strain values. Strain values exceeding

2500 microstrains are associated with unacceptable structural performance in all but the most lightly traffic and short-term roads. When specifying an appropriate mechanistic structural design, the thickness of the base layer is adjusted to maintain layer strain values below the recommended maximum values. Data from Fig. 8 can be used to assist in selecting a limiting strain value, according to the category of road to be built, based on operating life of the road, traffic volumes and performance index. In addition, to prevent excessive damage to the wearing course, deformation at the top of this layer must be limited to no more than 3mm.

Software is then used to generate a solution to base layer thickness requirements, to limit vertical compressive strain at the top of the in-situ layer to a value prescribed by the category of haul road. Fig. 9 illustrates one such solution, in this particular case for a 3-layer model in which various in-situ layer modulus values are encountered, together with a base layer of 3000MPa modulus (selected blasted waste rock) and 200mm thickness of 350MPa wearing course. The solution is based on wheel loadings generated from a Caterpillar 797B haul truck, loaded to manufacturers specified gross vehicle mass and operating with 800kPa tire pressure.

Functional Design Guidelines

The USBM guidelines provided the first insight into haul road functionality through consideration of general road performance. The primary characteristics considered were road adhesion and rolling resistance and the most practical construction materials recognized were asphaltic concrete, crushed stone or gravel and stabilized earth. The concept of functionality was not specifically introduced but rather alluded to in terms of some of the defects reported with these various construction materials. In conclusion, they recommended crushed stone or good quality natural gravel as wearing course materials, together with specifications for gradation and Atterberg limits.

The most common wearing course material for haul roads remains compacted gravel or gravel and crushed stone mixtures. In addition to a low rolling resistance and high coefficient of adhesion, their greatest advantage over other wearing course materials is that roadway surfaces can be

constructed rapidly and at relatively low cost. As with structural designs, if local mine material can

be used for construction, the costs are all the more favorable. This cost advantage is, however, not

apparent in the long term if the characteristics of the wearing course material result in an inherently

unsafe and maintenance intensive road.

By relating wearing course performance in terms of safety-critical defects (derived from an

analysis of those road design factors implicated in haulage accidents, following Thompson and

Visser; 2006), the defects most commonly associated with mine haul roads, in order of decreasing

impact on haulage safety and operational performance are typically;

- Skid resistance - wet, Skid resistance - dry, Dustiness, Loose material, Corrugations, Stoniness -
  loose, Potholes, Rutting, Stoniness - fixed, Cracks - (slip, longitudinal and crocodile).

By examining which wearing course material property parameters lead to these defects, a

specification was developed for wearing course materials selection (Thompson and Visser; 2006).

The specifications are based on an assessment of wearing course material shrinkage product (Sp)

and grading coefficient (Gc), defined in Eqs. (4) and (5) as;

$$Sp \quad = \quad LS \; x \; P425 \qquad (4)$$

$$Gc \quad = \quad \frac{(P265 - P2) \, x \, P475}{100} \qquad (5)$$

where;

LS $\quad = \quad$ Bar linear shrinkage (%)

P425 $\quad = \quad$ Percent wearing course sample passing 0.425mm sieve

P265 $\quad = \quad$ Percent wearing course sample passing 26.5mm sieve

P2 $\quad = \quad$ Percent wearing course sample passing 2mm sieve

P475 $\quad = \quad$ Percent wearing course sample passing 4.75mm sieve

The parameters comprising Eq. 4 and Eq. 5 are determined from road-building material indicator tests, as prescribed by the relevant testing methodology, such as ASTM (1998).

To select a suitable wearing course material, the selection chart in Fig. 10 can be used in which the two selection parameters that describe the material; the grading coefficient (Gc) and shrinkage product (Sp), define a range of acceptable specifications. A wearing course material that satisfies the specification is thus centered on an area bounded by a grading coefficient of 25-32 and a shrinkage product of 95-130 in which the overall and individual defects are minimized (Area 1). Extending this region to encompass poorer (but nevertheless operable) performance enables an additional area (Area 2) to be defined. If the three most critical haul road defects are considered, it appears that mine road-user preference is for much reduced wet skid resistance, dust and dry skid resistance defects. This is also borne-out with reference to the most common causative factors in haulage accidents, in which dust, visibility and stoniness figured significantly.

The selection should also be evaluated in the light of other material property limits identified as important in functional performance but not directly assessed in Fig.10. Table 1 presents a summary of these property limits, determined from road indicator tests of a wearing course material. Ideally, a suitable wearing course material should not exceed the parameter limits established in Table 1.

Maintenance Design

The maintenance aspect of haul road design cannot be considered separate from the geometric, structural and functional design aspects since they are mutually inclusive. Design and construction costs for the majority of haul roads represent only a small proportion of the total operating and maintenance costs incurred over the road's life. It is possible to construct a mine haul road that requires virtually no maintenance over its service life, but this would entail excessive expenditure on initial construction costs, although on-going road maintenance and vehicle operating costs would be low. Conversely, a maintenance intensive road, whilst much cheaper to build, would entail higher on-going maintenance costs and, as a result of rapid traffic-induced deterioration (i.e. rolling

resistance increases) higher vehicle operating costs over the life of the road. An optimally safe and efficient road design will include a certain amount and frequency of maintenance (watering, grading etc.) and thus maintenance can be planned, scheduled and optimized within the limits of required road performance and minimum vehicle operating and road maintenance costs.

Road maintenance itself is rarely implicated as a contributory factor in mine road accidents. This is because maintenance is seen as a reactionary measure, a maintenance activity, (blading, grading, watering, etc.) being initiated when road performance becomes unsatisfactory. However, if the geometric, structural or functional design components are incorrectly formulated at the design stage, a road will invariably become maintenance intensive as a result and frequent maintenance interventions will be required. Routine maintenance per se will not correct the underlying road design deficiency, only temporarily reduce it's impact on safety and operational efficiency. Hence in this discussion, maintenance management system design (Thompson and Visser; 1999, 2003) should not be considered as a universal remedy for poor road design in the first instance and the root-cause of road under-performance should be sought in the geometric, structural or functional design components.

Conclusions

Well designed and maintained haul roads are the key to minimizing truck haulage on-road hazards and costs, as well as increasing productivity. However, practically designing and managing a haul road for optimal performance is often difficult to achieve. We can be guided on this endeavor by our understanding of how a road design is developed, and, critically, the interplay between a good design and safe, cost efficient haulage.

The seminal USBM work of Kaufman and Ault in 1977 was the starting point of a formalized approach to mine road design. Just as the authors of the original USBM guidelines recognized that the development of surface mine haulage equipment had outstripped mine road design technology,

the continuing increase in truck size to-date, together with more recent powered haulage accident and incident analyses, has warranted further development of mine road design guidelines.

Augmented design and management guidelines have been developed over the past decade, both in response to the requirements of mine operators for more safe and efficient haulage systems, and the truck manufacturers' requirements for a more predictable and controlled operating environment. Amending existing or developing new mine road design methodologies requires an analysis of surface (powered) haulage accident and incident records to identify the major contributory factors that led to these accidents. Several studies are summarized from which it was seen that the principal sub-standard surface mine road design factors were geometric and functional design issues, with a lesser, but nevertheless significant contribution from inadequate structural design.

Whilst improved mine haul road design can reduce haulage accidents, recognition also needs to be given to human factors which are a significant contributor to haulage accidents. The human factor interactive effects include the geometric, structural and functional design components and to prevent an accident or reduce the severity of its consequences, a road should be more accommodating to human error. The more that is known about human error in the context of mine haulage, the better a road can be designed to accommodate those actions or non-standard practices that would, on a poorly designed road, invariably escalate an error into an accident.

References

AASHTO (American Association of State Highway and Transportation Officials. 1982. AASHTO Materials, Part 1, Specifications. Washington, DC., USA.

ASTM (American Society for Testing and Materials). 1998. In *Annual Book of ASTM Standards*, Sec 4, Vol 04.08, West Conshohocken, PA., USA: ASTM International.

Aldinger, J.A., Kenney, J.M. and Keran, C.M. 1995. Mobile Equipment Accidents in Surface Coal Mines. USDOI Bureau of Mines IC 9428.

AUSTROADS. 1994. Road safety audit. National Association of Road Transport and Transport Authorities of Australia, AUSTROADS Publication AP-30/94, Sydney, Australia.

AUSTROADS. 2009. Review of Relationship to Predict Subgrade Modulus From CBR. National Association of Road Transport and Transport Authorities of Australia, AUSTROADS Publication AP-T130/09, Sydney, NSW., Australia.

Fesak G.M., Breland, R.M. and Spadaro, J. 1996. Analysis of Surface Powered Haulage Accidents. Mine Safety and Health Administration, USDOL HAS Bulletin. http://www.msha.gov/PROGRAMS/HSAPUBS/SURPOWER.pdf. Accessed 1.11/2009.

FHWA. 1985. ELSYM5A: Interactive version 5A users guide. FHWA, US Dept of Transportation.

Fourie G.A.F., Smith, R.A.F., Thompson R.J. and Visser A.T. 1998 Benchmarking haul road design standards to reduce transportation accidents. *International Journal of Surface Mining and Reclamation Engineering*, vol 12, n4, December, pp157-162.

Miller R.E., Thompson R.J. and Lowe N.T. 2004. A GPS-based system for minimizing jolts to heavy equipment operators. *Society of Automotive Engineering, SAE Transactions, Journal of Commercial Vehicles*, SAE 2004-01-2726, ISBN 0-7680-1641-X, pp850-855.

MinCad. 2008. CIRCLY 5. Mincad Systems Pty Ltd, Richmond, Vic., Australia.

Randolph, R.F. and Boldt, C.M.K. 1996. Safety analysis of surface haulage accidents. *Proc 27th Annual Institute on Mining Health, Safety and Research*. Blacksburg, VA: Virginia Polytechnic Institute and State Univ. p:29-38

Thompson R.J. and Visser A.T. 1996. Towards a mechanistic structural design method for surface mine haul roads. *Jnl. South African Institute of Civil Engineering*, 38:2, second quarter, Johannesburg, South Africa.

Thompson, R.J and Visser, A.T. 1999. Management of unpaved road networks on opencast mines. *Transportation Research Record (TRR) 1652,* Transportation Research Board, Washington, D.C.

Thompson R.J. and Visser A.T. 2003. Mine haul road maintenance management systems. J*nl. of the South African Institute of Mining and Metallurgy*, 103:5, May/June.

Thompson R.J. and Visser A.T. 2006. Selection and maintenance of mine haul road wearing course materials. *Trans(A) (Mining Technology) Institute of Mining, Metallurgy and Materials (IMMM).* 115:4, pp140-153

USBM. 1977. The Design of Surface Mine Haul Roads - A Manual. USDOI Bureau of Mines IC 8758.

USBM. 1981. A Study of Mine Haulage Roadway Surface Safety Hazards. USDOI, Mines, Minerals, Health and Safety Technology Division, Bumines OFR 5-83.

Thompson, RJ. 2010. In *SME Mining Engineering Handbook*. Edited by P Darling. Ch.21 (12.3). Design, Construction and Maintenance of Haul Roads. Littleton, CO., USA: SME. Forthcoming.

Thompson, RJ. 2010a. CBR and mechanistic structural design methodologies for mine haul roads. Submitted to *Trans(A) (Mining Technology) Institute of Mining, Metallurgy and Materials (IMMM)*. Forthcoming.

Figure 1. Typical integrated approach to road design.

Figure 2.   Surface coal haulage truck accident categories (after Aldinger et al; 1995).
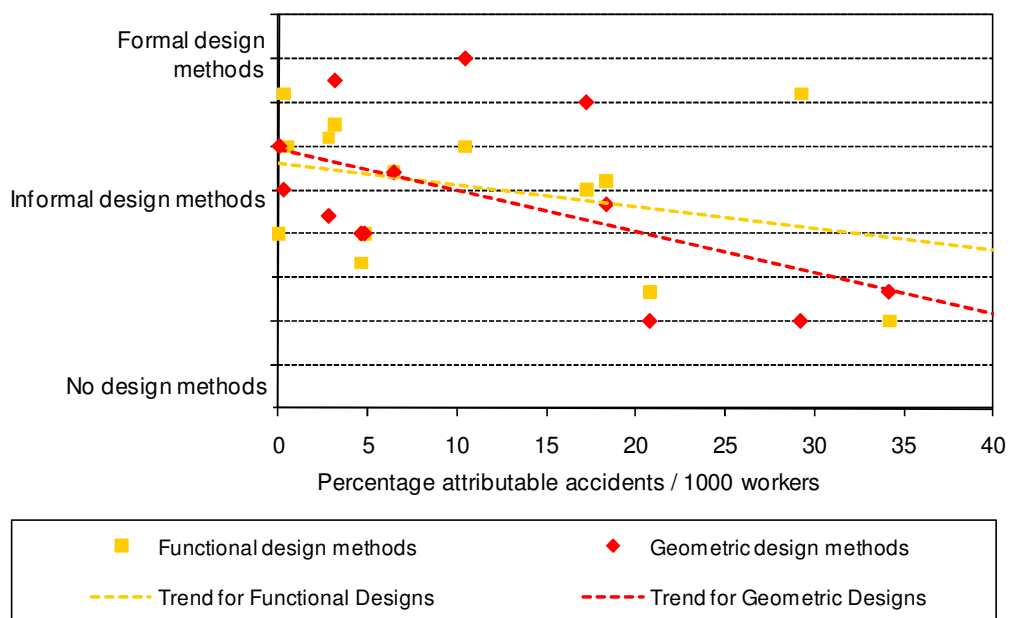

Figure 3.   Relationship between road design and attributable accident rates (South Africa).
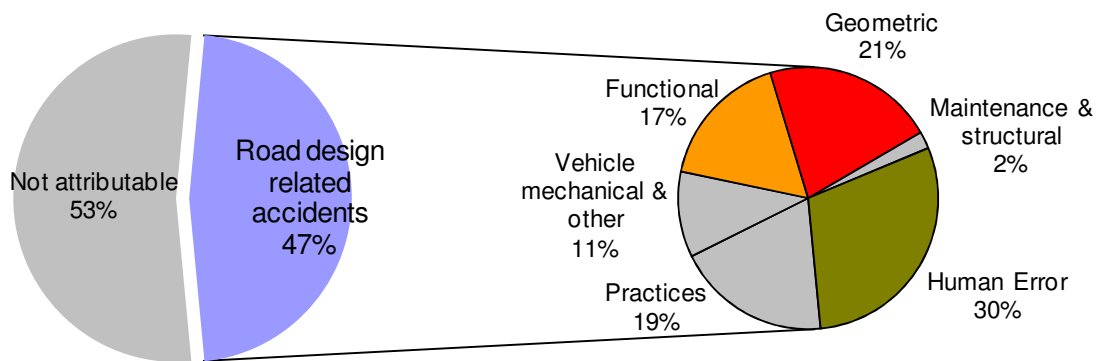
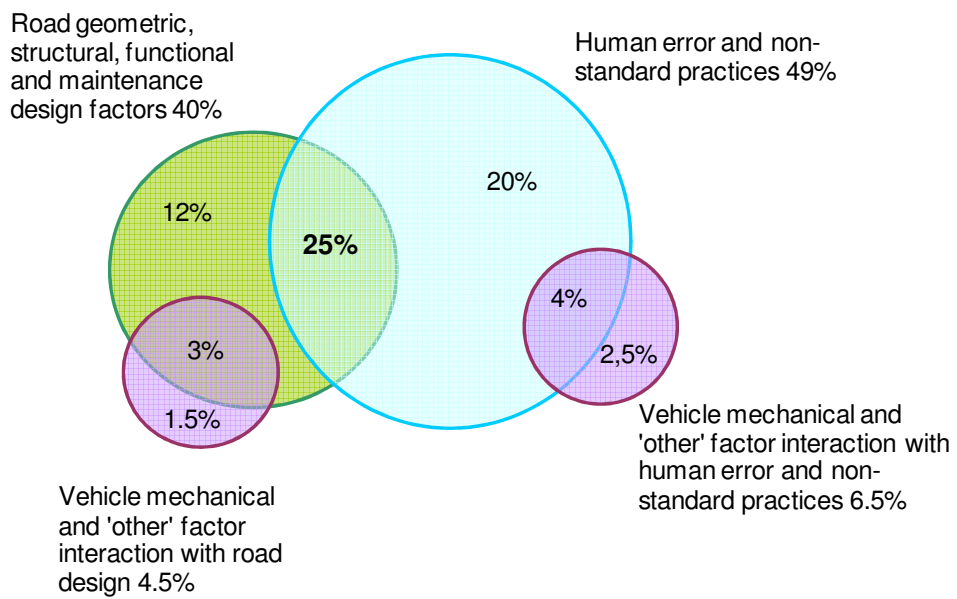**Figure 4**   Role of road design in attributable accidents (after Fourie et al; 1998)

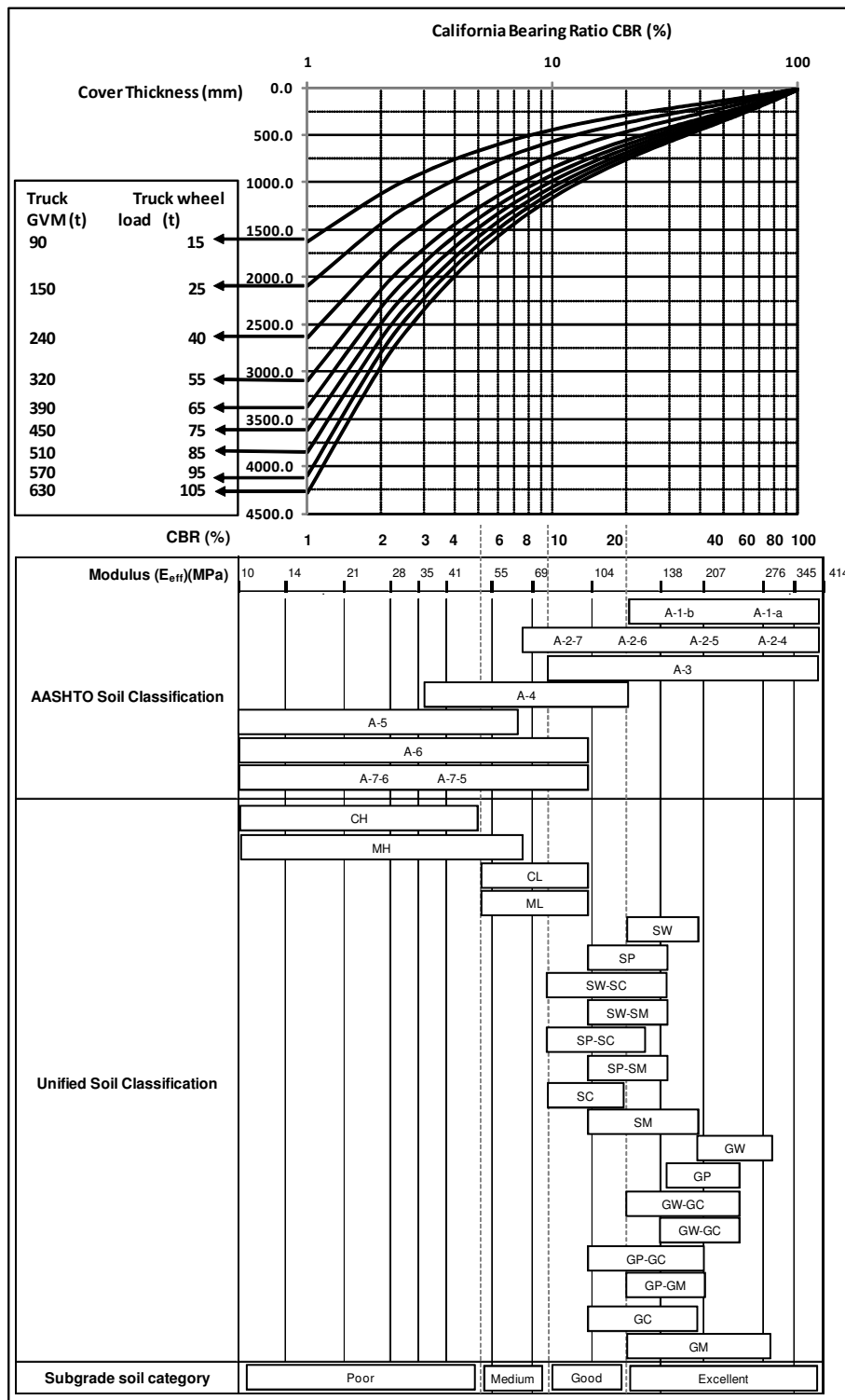**Figure 5**   Factor interactions contributing to truck haulage accidents.

Figure 6 CBR cover curves for 90-630 metric ton GVM haul trucks and approximate bearing capacities of various soils types defined by the Unified Soil Classification (ASTM; 1998) and American Association of State Highway Transportation Officials'(AASHTO; 1982) systems.
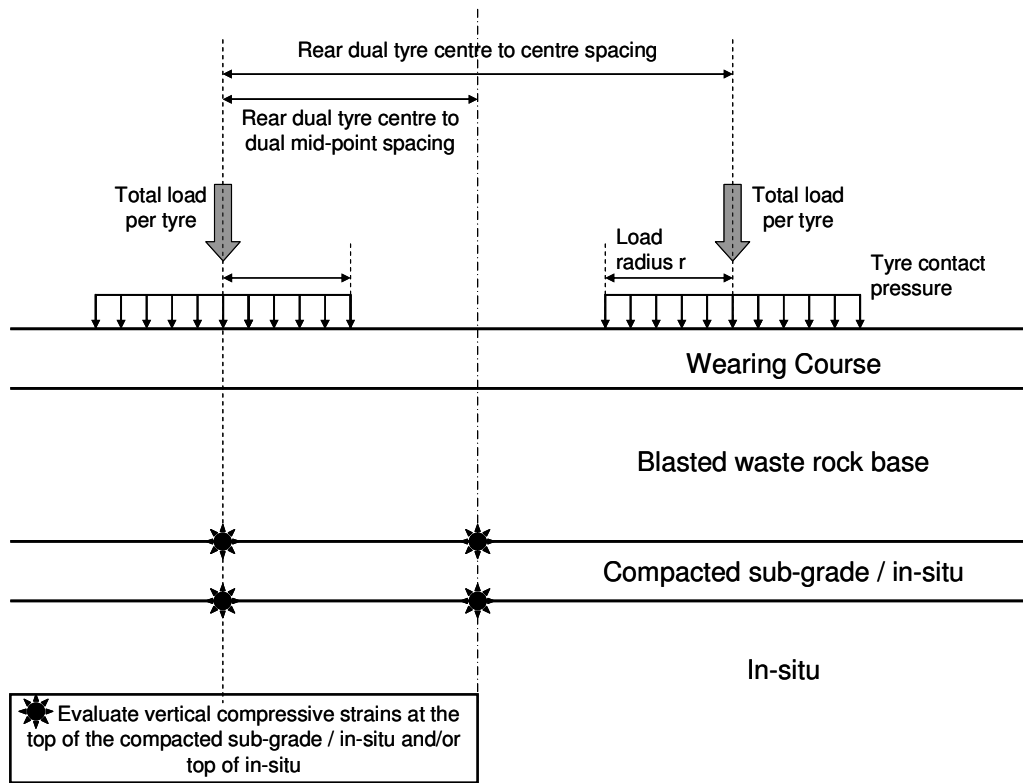
Figure 7. Multi-layer model for mechanistic structural design evaluation

Haul Road Category	Typical Description	Range of maximum permissible vertical compressive strains (µstrains)		
		Traffic volumes > 100kt/day	Traffic volumes < 100kt/day	

Limiting pavement layer vertical compressive strain values for mine haul road structural design

Haul Road Category	Typical Description	Traffic volumes > 100kt/day	Traffic volumes < 100kt/day
CATEGORY I	Permanent life-of-mine high traffic volume main hauling roads and ramps in- and ex-pit. Operating life >20 years	900	1500
CATEGORY II	Semi-permanent medium- to high traffic volume ramp roads in- and ex-pit. Operating life >10 years	1500	2000
CATEGORY III	Shorter-term medium- to low-volume in-pit bench access, ex-pit dump, or ramp roads. Operating life; • <5 years at >50kt/day) • <10 years at <50kt/day)	2000	2500

Maximum permissible vertical strains can also be determined from (*kt/day x performance index*) where performance index is defined as;
1 Adequate but fairly maintenance intensive
2 Good with normal maintenance interventions
3 Outstanding with low maintenance requirements

Figure 8   Haul road classification and associated mechanistic structural design limiting strain
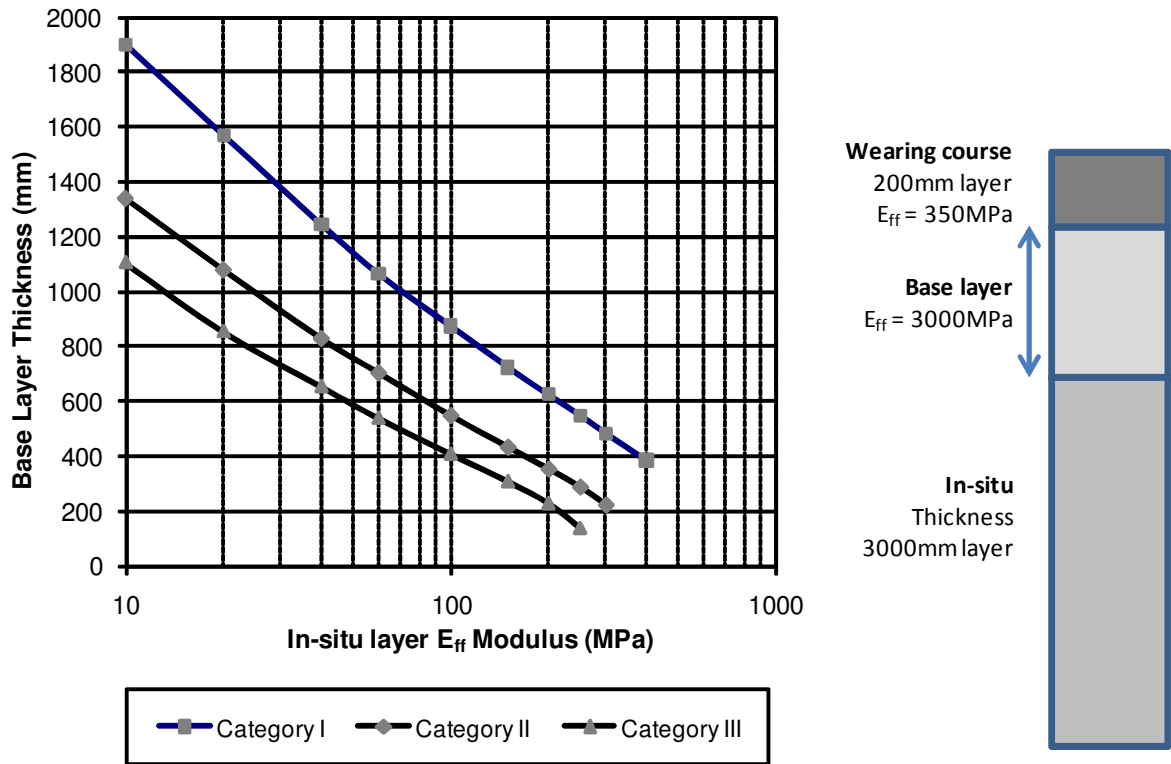
criteria

Figure 9 Typical mechanistically determined multi-layered elastic solution to base layer thickness for CAT 797B fully laden truck, for category I-III haul roads.
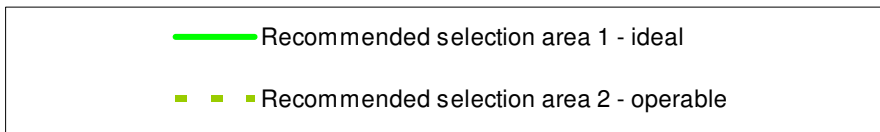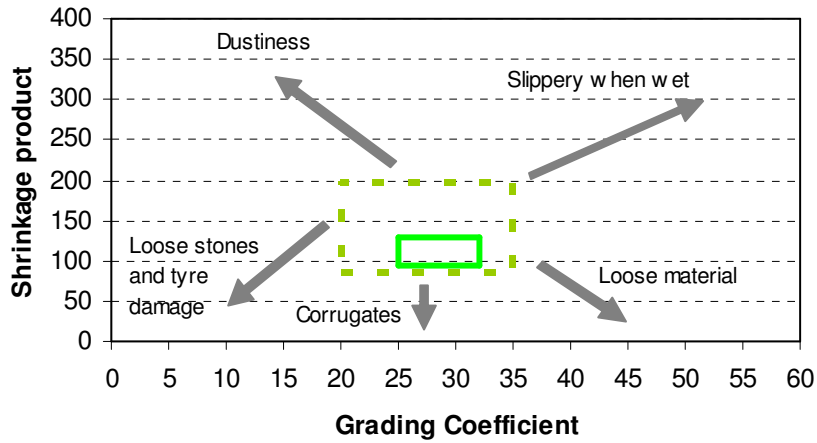
Figure 10   Haul road wearing course material selection (after Thompson and Visser; 2006).

Table 1. Additional wearing course material selection parameters (after Thompson and Visser; 2006).

Material Parameter	Range	
	Min	Max
Shrinkage Product	85	200
Grading Coefficient	20	35
Dust Ratio[1]	0,4	0,6
Liquid Limit (%)	17	24
Plastic Limit (%)	12	17
Plasticity Index	4	8
4-day soaked CBR at 98% compaction	80	
Maximum Particle Size (mm)		40

[1] Dust ratio defined as;

$$\frac{P075}{P425}$$

where
P425 = percentage of material passing the 0.425mm sieve
P075 = percentage of material passing the 0.075mm sieve