Introduction

These notes introduce the concepts & principles of mine haul road design, from philosophy of provision, road rolling resistance, road building material selection and characterisation, road-user (truck and traffic) requirements, through to performance benchmarking and evaluation as a basis for road maintenance management decision making.

These notes will assist in the design and evaluation of current and proposed haul road systems and to identify and rectify road design deficiencies. They form the basis of a haul road continuous improvement strategy to reduce cost per ton hauled across the mine road network. The notes provide answers to practical mine haul road design and operational issues such as;

- why are good roads necessary - what are the benefits of an improved haul road infrastructure?
- what critical operational aspects should a road design consider?
- equipment, materials and methods - what is required?
- how do you translate a design into practical construction techniques?
- when are dust palliatives appropriate - and how do you select suitable products and applications?
- how do you benchmark a road design -

- what do you see, what does it mean and how do you identify the root-cause of a road problem?
- how can you determine road rolling resistance and identify the means of reducing it?

Following a general introduction to terminology, resources and road classification, design considers the aspects of;

- generic haul road geometric design for optimum road and truck fleet performance
- structural and layerworks design concepts and evaluation techniques
- functional design, incorporating wearing course material selection and dust palliative selection and management
- benchmarking and performance evaluation techniques which can be used as a basis for motivating and implementing haul road maintenance or rehabilitation.
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INTRODUCTION TO Haul Road Design and Construction

Basic Design Requirements For Haul Roads

In truck-based hauling systems, the mine haul road network is a critical and vital component of the production process. As such, under-performance of a haul road will impact immediately on mine productivity and costs. Operations safety, productivity, and equipment longevity are all dependent on well-designed, constructed and maintained haul roads. The mine haul road is an asset and should, in conjunction with the haul trucks using the road, be designed to deliver a specific level of performance and its routine maintenance managed accordingly.

A well-built and maintained haul road will enable haul trucks to operate safely and efficiently. Poor roads pose safety problems for not just haul trucks, but also all road-users. A well-designed, constructed and maintained haul road has significant advantages for a mining operation, not the least of which are:

- The provision of safer driving conditions and a reduction in traffic hazards;
- Reduced truck operating costs, faster cycle times: higher productivity and lower cost per ton hauled;
- Reduced road maintenance costs, less spillage, less water damage due to accumulation, reduced dustiness and longer road service life;
- Less stress on drive train, tyres, frame and suspension: higher asset utilisation and component life, lower life-cycle costs;
- Improved tyre and rim life.
Empirical Design

Many mine roads are designed empirically, relying heavily on local experience. This experience, while locally relevant and often delivering adequate mine haul roads eventually, does not lend itself to an understanding of the road design process and, more importantly, if the haul road performance is sub-standard, does not easily allow the underlying or root-cause of the poor performance to be identified.

An ad-hoc or empirical approach to haul road design is generally unsatisfactory because it has the potential for over-expenditure, both on construction and operating costs, arising due to:

- Over-design and specification, especially in the case of short term, low-volume roads where the effect of rolling resistance, although minimised, does not contribute significantly to reducing total road-user costs across the mine’s network of roads due to the higher initial construction cost; or

- Under-expenditure on road construction, leading to premature failure; excessive truck operating costs; loss of productivity and, in the case of longer-term, high volume roads, high contributory costs from rolling resistance effects. Under-designed roads are often maintenance intensive, so much so that even well built roads appear to perform poorly, due to maintenance being postponed on these roads to accommodate the intensive maintenance requirements of the under-designed roads.

Economy of scale and the increase in haul truck payload has so far seen the ultra-class truck (220t and larger) population rise to over 40% of all mine trucks used. With this increasing size, haul road performance can be compromised, resulting in excessive total road-user costs. These are often seen directly as an increase in cost per ton hauled, but are also seen indirectly as a reduction in production rates and vehicle and component service life and availabilities - translating to increased life-cycle costs. Truck haulage costs can account for up to 50% of the total operating costs incurred by a surface mine and any savings generated from improved road design and management benefit the mining company directly as reduced cost per ton of material hauled.
Surface Mining Costs
Open pit mining 250kt/day 500m depth

- Hauling
- Haulage Support
- Loading
- Drilling/Blasting
- Admin & Other
**Rolling Resistance - Manage and Minimise**

Central to the cost of truck hauling is the concept of rolling resistance (expressed here as a percentage of Gross Vehicle Mass (GVM)). Rolling resistance is also expressed in terms of kg (or N) resistance per ton of GVM, where $10\text{kg/t} = 1\%$ rolling resistance or $1\%$ equivalent grade.

It is a measure of the extra resistance to motion that a haul truck experiences and is influenced by tyre flexing, internal friction and most importantly, wheel load and road conditions. Empirical estimations of rolling resistance based on tyre penetration specify typically a $0.6\%$ increase in rolling resistance per centimeter tyre penetration into the road, over and above the $1.5\%$ (radial and dual wheel 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.

In general terms, when using truck manufacturers performance charts for up- and down-grade hauling evaluations;
Grade against the load (up-hill);
**Effective grade (resistance) % = Grade % + rolling resistance %**

Grade with the load (down-hill);
**Effective grade (resistance) % = Grade % – rolling resistance %**

Taking an electric-drive rear-dump truck of 376t (GVM) as an example, on a ramp road of 8-10% grade and a basic rolling resistance of 2%, an additional 1% rolling resistance will reduce truck speed by 10-13%.

On a flatter surface road of 0-2% grade and a basic rolling resistance of 2%, an additional 1% rolling resistance will reduce truck speed by between 18-26%.

The penalty associated with increased rolling resistance is clear – so, conversely, small reductions in rolling resistance can lead to significant improvements in vehicle speed and productivity.

With these significant benefits derived from reducing road rolling resistance, how do you go about developing a business improvement strategy based on targeted improvements to the haul road network? Clearly, the improvement strategy must be based on a formal assessment of the mine’s roads, to identify design deficiencies as part of a broader approach to traffic management and safety (of which design is a component).

With regard solely to the benefits of improved road design, the various solutions that enhance productivity need to be viewed holistically. For instance, trolley-assist may improve cycle times and reduce cost per ton hauled, but it is first necessary to review design and management of the road, before resorting to solutions that do not directly address the root-cause 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 design improvement and, once optimised, revert to resource supplementation to leverage these benefits through optimal asset and resource interaction.
An Integrated Design Approach

Many concepts from highway engineering can be adapted to the design, construction and management of mine roads. However, significant differences in applied loads, traffic volumes, construction material quality and availability, together with design life and road-user cost considerations, make the requirement for a tailored design solution readily apparent. Designing a sound and safe 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 increased 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 of the road infrastructure must be correctly addressed at the design stage.

**Geometric design**

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 (road width, curve radius, etc.) and vertical (ramp gradients, cross-fall/camber, super-elevation etc.) plane, stopping and sight distance requirements, etc., within the limits imposed by the mining method.

The ultimate aim is to produce an optimally efficient and safe geometric design. Considerable data already exists...
pertaining to 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.

**Structural design**

The structural design will provide haul road ‘strength’ to carry the imposed truck wheel loads over the design life of the road without the need for excessive maintenance. Poor quality roads are often caused by deformation of one or more layers in the road - most often weak, soft and/or wet materials below the road surface.

**Functional design**

The functional design is centred on the selection of wearing course, sheeting (or surfacing) materials where the most suitable choice is required which minimises the rate of degeneration, or rolling resistance increase, in the road surface.

Defects on the road arising due to poor functional design, such as that shown here, will cause damage to the truck, in this case the tyre carcass, rim, front strut and possibly front cross-member which are all liable to premature failure under the conditions shown here.

A road with many ‘defects’ often has a high rolling resistance.

**Maintenance design**

The maintenance design identifies the optimal frequency of maintenance (routine grading) for each section of haul road in a network, thus maintenance can be planned, scheduled and prioritised 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.
A poor road will always require a lot of repair - or 'maintenance' - work to be done. This will slow the trucks due to both poor road conditions and the maintenance work itself. An often cited statistic is that once a road has deteriorated, it takes 500% more time to fix it than it took to originally build. The better the roads are built, the slower the deterioration rate and the less maintenance will be required.

A little time and effort spent in building to 'specification' will result in long term benefits - reduced repair work and better performance. A well-built and cost-effective haul road lies somewhere between the extremes of:

- Design and build a road that needs no repair or routine maintenance over its life - very expensive to build, but cheaper to operate; or
- Build a road with very little design input, that needs a lot of repair, a high-intensity of maintenance and rehabilitation over its life - very cheap to build, but very expensive to operate.

This is where an integrated approach to mine haul road design pays dividends - designing a road to be built and maintained over its operating life at the lowest overall (build and operate) cost.
Truck Related Design Requirements

There are several types of haul truck often used by mines - and a road design starts by considering basic truck specifications, operating philosophy and road design requirements, as follows:

**Articulated dump truck (ADT)**

These trucks are often used on short-term mining or civil contracts and as such can be run on ‘poorer’ roads. Their articulation, drive system, small wheel loads 7-12t and high wheel surface contact area mean that even a haul road built without a structural design will probably be trafficable after several months by these vehicles - albeit at high rolling resistance. Lack of a formal functional design will also lead to high rolling resistance - and other defects such as dust will also reduce fleet productivity eventually. In the final analysis, it is necessary to evaluate the cost-benefits of cheap (or no) road building against reduced fleet efficiency and high cost per ton hauled. In broad terms, the longer the haul contract, the more effort should be invested into a formal road design and road maintenance program.

**Rigid-body rear dump truck (RDT)**

The rigid body truck type, commonly a 2-axle rear dump truck, is much more dependant on good haul road conditions than the much smaller ADT. The frame is rigid and thus less flexing can take place in response to uneven roads. However, on a well-built and maintained haul road they are highly cost-effective where the length of the haul cycle is limited.

**Bottom-dump truck (BDT)**

A bottom dump truck uses a separate trailer, hauled by a tractor unit, which would be similar in design to the RDT - minus the dump body. Again, good roads are critical to the cost-effective application of these hauler types - perhaps more so where units have a smaller kW engine power to GVM ratio than RDT’s. Poor performance will become evident on steep ramp roads if the rolling resistance is high.

**Road-trains**

These can either be modified trucks designed for use on public roads or purpose built multi-powered units specifically designed for long hauls in mining. The main aim with these trucks is to take advantage of their cost-effectiveness and speed on long hauls of many kilometres. A road design used with these trucks, while obviously needing the structural capacity, must also have excellent functional design, since the combination of speed and road defects magnifies any damage to the truck - and any road defect that would slow the truck (e.g. dust, corrugations, ravelling, etc.) or present safety hazards at speed (slipperiness when wet, etc.) defeats the purpose of using these trucks in the first place.
‘Design’ or Just ‘Build’ A Road?

Who designs the roads built at your mine? Do you have a head-office or mine planning department who supply pre-planned designs or specifications for road building?

Or, is it simply “we need to access block 7N for loading today, so push a road into the block for us?”

Your road design crew is then the dozer operator who maybe hasn’t had any formal road-building training and has no basic road design standards to work from. There are some straightforward road construction ‘do’s and don’ts’ that can easily up-skill an operator, making the road-building process more time- and cost-effective - with a better final result.

Does this sound a lot like how your mine builds roads? What can go wrong? Let’s look at one simple example.

The diagram shows a longitudinal section through the road built, and now the trucks start using the road. How long does it take the truck to cycle up the ramp under these conditions?

Assume a 380t class of RDT, running up the ramp as shown, where the grade of the road varies between 8% and 13%, with a 3% rolling resistance. With this road ‘design,’ a fleet of 7 trucks could produce 340tons per truck-hour. However, excessive transmission shifting on the laden haul (due to the grade breaks) will reduce engine, drive-train wheel motor and tyre life and on the return trip, retarder overheating will occur.

However, by removing the grade-breaks (using a constant 10.3% grade from bottom to top), with the identical 3% rolling resistance, 470tons per truck-hour can be produced – an
increase of 38% or 500,000 tons per annum. If an annual excavation target of 10Mt tons were set, by using an improved road design and construction guideline, the same target could be achieved with 5 instead of 7 trucks. This performance can be further improved when rolling resistance is reduced from 3% to 2%.

How rolling resistance impacts your haul fleet productivity depends on various factors, including grade of haul, truck type and model (electric or mechanical drive, type of engine), and load carried. A good rule of thumb for an ultra-class truck (with approx. 4.2kW/t of GVM) is that:

- A 1% increase in rolling resistance equates to a 10% decrease in truck speed on ramp, or a 26% decrease in speed on the flat.
The roadway or road alignment has to provide a carriageway (or lanes) for trucks and also incorporate shoulders (for breakdowns, parked vehicles, etc.) and drainage.

Using the diagram above, the roadway width is, strictly speaking, referred to as pavement width. The carriageway width (for the dual lane design shown above) extends to include the shoulders at the edges of the road, whilst the formation width includes the roadside verge, safety berms/bunds and drains in addition to the above. Formation width will be related to the height of earthworks above or below the natural ground level on which the road is built.

Working up through the layers (courses) below the haul road;
**Sub-grade / In-situ**

The prepared portion of the formation at natural ground level is referred to as sub-grade. This is the in-situ material on which the road is built. The softer the in-situ material is, the thicker the subsequent layer(s) must be to protect the in-situ. Poor protection or ‘cover’ means that the in-situ will deform under the wheel loads of the trucks and the road will become very uneven. Because this layer is at the bottom of the road, it is expensive to repair these layers when problems arise. However, when using appropriate Structural Design Specifications, this would accommodate various types of in-situ material and how to ‘cover’ or place layerworks above them for adequate ‘protection’ to prevent premature failure.

**Fill**

Sometimes referred to as sub-grade, if the in-situ is not level, fill is often used to level the construction surface before road-building starts. It is easier to build a road once the in-situ or fill is level (or ‘on-grade’) and the cross-sectional shape or ‘road-prism’ is established at this level in the layerworks.

**Sub-base**

This is the layer above grade or in-situ. A well-drained stable road base is one of the most important fundamentals in road design. If the layers beneath the road are not strong or rigid enough, rutting, potholing and deformation will always occur. When using a mechanistic design method for unpaved mine roads, the base and sub-base are combined in a single layer comprising selected blasted waste rock. If using a CBR-based cover-curve design approach, then the sub-base will comprise material somewhat ‘softer’ than the base and, with the CBR design method, a selected blasted waste rock layer can’t be used (analysed). The sub-base provides a working platform upon which overlying layerworks can be compacted.

**Base**

This is the layer immediately below the wearing course. It is important because it ‘protects’ the softer material below (in-situ or fill) from the weight of the truck running on the wearing course. The weight (or load) of a haul truck, when applied to a weak, soft in-situ or fill, will cause this material to displace and eventually deform, resulting in rutting, potholes and other similar ‘structural’ defects. Selection and placement of the base layer is based on the Structural Design Specifications.

**Wearing course**

This is the layer of material on the top of the road - also called surfacing or sheeting. For mine roads it is often an (unbound) gravel mixture - but exactly
what that mixture comprises is important - because the wearing course controls how the road performs and how the road-user interacts with the road (skid resistance, traction, etc.). Both safety and productivity are influenced by the wearing course ‘performance’. When a road is ‘maintained’ or bladed (scraped), it is the wearing course we work with, to restore it to its original condition and remove surface ‘defects’ which, in part, contribute to rolling resistance. Selection and placement of this layer is based on the Functional Design Specifications.
Components of an Integrated Road Design

Why An Integrated Design Approach?

In addition to terms that relate to what we are building, there are some terms that relate to how the specific design activities, associated with what we are going to build, are applied. To make the road-building methodology easier (and, if the design is simple - building the road according to the design is often easier too), design is split into a number of individual ‘components’.

These components are integrated with each other - they follow a logical sequence and are inter-dependant. If one design component is not correctly addressed at the design stage - no amount of remedial work in another component will correct the underlying design deficiency.

As an example, look at the sharp curve (switchback) shown in the Figure.

Immediately, the wearing course (surfacing) looks suspect - the road condition requires maintenance to be carried out frequently. But is poor wearing course material, or functional design really at fault? Probably not - the geometric design of the curve is incorrect (radius too tight - close to the limiting truck turning circle radius) resulting in scrubbing of the innermost rear tyre of a dual assembly as the truck runs through the curve. There also appears to be no (or possibly incorrectly applied) super-elevation and there could be drainage issues seen in the upper LH corner of the curve.

Eventually, the wearing course will be sheared off to the outside of the bend and the blasted rock (base or in-situ) under the road exposed - and on switchbacks like this tyre damage will certainly result. Simply blading the road is not an adequate response - poor geometric design is the root-case for the under-performance here.
So, given the fact we need to ensure we address all the components of a road design adequately, how do you make sure you address each design component fully? The key lies in using an integrated approach to road design, illustrated here.
Geometric Design

Once the basic road design data or parameters are established, the geometric design is the starting point of the 'integrated' approach to road design.

Geometric design refers to the layout and alignment of the road in:

- The vertical plane - here we design for safe and efficient
  - sight and stopping distances, and
  - incline, decline or ramp gradients; and

- The horizontal plane - here we design for safe and efficient
  - width of road,
  - curvature of bends,
  - switchbacks - switchbacks are always problematic in road design - slow and tight radius bends alike,
  - super-elevation (banking),
  - run-out,
  - camber or cross-fall, and
  - intersection location.

Also included in the geometric design are the following:

- Berm walls

A 'new jersey barrier' type berm at the edge of the road - but what is the design requirement - stop the truck or warn the
operator of misalignment? In this case, these ‘berms’ may only temporarily deflect a truck – and could create additional hazards too. Median (road centre or splitter) berm designs are also considered in under this design component.

Drainage

Water on the road. No matter how good the design, water will always damage a mine road. Keep water OFF the roads - or at the very least lead water off the road as soon as possible - but without causing cross-erosion of the wearing course. A critical component of any geometric design is a terrain map showing elevation contours and drainage directions around the road. Make sure water is led away from the road and don’t just let it seep into the in-situ. As will be seen later - water weakens the road layers and can be a source of many road defects.

Structural Design

This refers to the design of the road layerworks - this is normally done once the geometric design is complete.

As seen here, the base placed directly on top of (compacted) in-situ must prevent the softer in-situ from being too near the road surface where it may be susceptible to deformation as a result of the applied wheel loads. This base layer (selected blasted waste rock) is end tipped, dozed into road prism shape (to accommodate camber (crown) or cross-fall) giving at least the minimum specified thickness across the carriageway and then compacted and blinded if necessary with crushed hard overburden to create the design thickness and critically, strength. This is one structural design option of many, the method selected being dependant to a large extent on the type of road-building materials anticipated.
Functional Design

This refers to the wearing course or sheeting; how to choose the best wearing course material, and how it will react to trucks travelling on it and the environment in which it operates.

Paramount here are considerations of:

- Dust generation, visibility of all road users, adequate sight distances, together with adhesion (traction) and dry skid resistance;
- Wet weather trafficability, wet skid resistance; and
- Minimising surface deterioration rates (or rate of increase in rolling resistance) and routine maintenance intensity.

Maintenance Design

As stated earlier, we cannot generally afford to build a mine road that requires no maintenance without recourse to very expensive materials and construction techniques. Often incorporating bituminous seals or asphaltic concretes (hot mix asphalt), these road designs should be assessed by a mine on a case-by-case basis to determine if the extra costs are warranted by increased traffic speed and reduced maintenance costs.

Longer term high traffic volume roads (ideally in conjunction with smaller haul trucks) are often easier to justify, but short-term, low volume roads are generally not cost-effective cases for sealing.

For an unsealed or unpaved (gravel wearing course) road, given the less-than optimal construction techniques and materials, what we can do is to estimate how much maintenance (blading, watering and regravelling) of the wearing course is needed and how often. The deterioration that occurs is generally closely associated with rolling
resistance, which, as discussed earlier, directly affects cost per ton hauled. The more rapidly a road deteriorates, the more rapid is the increase in rolling resistance.

If we understand how quickly a road deteriorates, we can plan how often we need to respond to that deterioration to ‘fix’ the road again (or reduce rolling resistance). Once we look at a network of roads, we can then begin to assign priorities to maintenance in terms of the cost-benefit of blading one road compared with another – the cost being the cost to fix the road, whilst the benefit being associated with improved road safety, reduced rolling resistance - increased haul speeds, reduced fuel consumption and ultimately reduced cost per ton hauled.
Road Construction Resources

What Do You Need To Make A Road?

A road is built according to a design, and that design forms the basis of:

■ Construction recommendations (what you should do), and
■ Method specifications (how you should do it).

You also need resources to make a road. These resources are typically:

■ Time - everything takes time - a good road takes time to build, but so does a bad road. What makes the difference is how the time is used - are you doing the right thing?
■ People - they must plan and do the work, and have the ability to evaluate what they have done - do you know if you are doing the right thing?
■ Equipment - it does the work - wrong equipment may appear to do the work, but it will either:
  • Take too long, or
  • Not do the work according to specification.
■ Materials - they form the road. Wrong materials may appear to be satisfactory, but when the road is built and the trucks are running, only then will you see your materials were inappropriate. We can select the materials we build with, but we can’t easily select the in-situ material on which the road is built.

All these resources cost money and a road design and road building project should aim to get the best ‘value for money’ from a combination of all these resources. In the road design specifications, equipment and materials are most often specified. In the next section we will look at these in more detail.

Equipment For Road Building

Large tracked dozer (D9 or larger, 45t, 300kW) and large wheel dozer (assist)

Used primarily for ripping and shaping in-situ and selected blasted waste rock base or in-situ (if road is built in-pit on blasted material) layers. The dozer must be able to shape the rock layer (base) on which the road is built. To do this, it must be able to rip the material loose if required, push it to profile (or grade) and remove oversize rock.

It must also be able to open and spread material tipped by dump trucks as part of the road building process. In doing this, the dozer will also start the process of compaction and will form a smooth surface on which the vibratory or impact roller will operate. The larger the dozer, the better the initial strength of the rock layer will be and compaction requirements will be reduced (but not eliminated).
The dozer would ideally need to use a GPS and computer-aided earthmoving system or similar to push the material in the road base or in-situ to the required profile. Remember that this profile should be aligned both in the horizontal and vertical planes.

A wheel dozer could also be used to assist the track dozer, but NOT as primary equipment. This is because the material breakdown caused by the dozer tracks is useful in preparing a finish to the base or in-situ layers - an effect not easily replicated by a wheel dozer.

**Compaction Equipment.**

Compaction is critical to the success of a road-building project. With small, light haul trucks on very short-term hauling operations, compaction is sometimes not required because the dozer can compact the layers sufficiently. However, when larger trucks are used, dozer compaction alone is not sufficient (since it does not compact deeper into the layers) and a large steel drum vibrating roller, impact (or grid roller as a last resort) is needed to shake the layers down, interlock the material, increase it’s density and ultimately it’s strength.

**Vibratory roller**

A large vibratory roller (230kN vibratory force) can assist in layer compaction - especially gravelly in-situ, fill, sub-base, base and wearing course. For the wearing course, a vibratory roller can be used with or without vibration, to compact the material. It is superior to any other type of compaction equipment in this layer.

**Impact roller**

Preferably, a large impact roller should be used for layerworks (especially selected blasted rock base layer) compaction - the advantage with this type of equipment is the
much reduced number of ‘passes’ required to achieve compaction - hence reduced construction unit costs. Typically, a 25kJ (or larger) impact roller would be used, towed by a large 4x4 tractor unit. The degree of compaction specified in a layer is usually ‘until no further movement is seen under the roller’. Alternatively, ‘intelligent compaction’ systems may be used to identify when layer compaction is complete, for instance (with steel drum rollers) Caterpillar’s Compaction Meter Value (CMV®) system or Bomag’s Evibe® method. Most contractors can supply impact rollers - however, it is also a useful piece of mine plant since it can be used to great effect in preparing waste dump roads, in compacting the tip head (top of dump tipping point), and blinding the bench floor in the loading area, which is always an area of potential tyre damage.

**Large grid roller**

Should not be used in a primary compaction role. A large vibratory grid roller helps break down larger material. The grid roller is also useful in wearing course preparation, if hard and slightly oversize blocky aggregates are used. The roller will breakdown the blocky material and compact it, resulting in a strong, wear and erosion resistant surface. However, this ‘breakdown’ does not occur very deep into the layer - so care must be taken if using this equipment that the oversize rocks are not just ‘hidden’ below a thin skin of finer material. If this is the case, the oversize will soon ‘grow’ out to the surface and make road blading difficult (due in reality to gravel loss to the roadside during trafficking and consequent exposure of the blocky material).

**Grader (16-24 ft blade length or similar)**

A grader is used during construction to:

- Open and spread layerworks material prior to compaction;
- Re-shape layerworks following compaction;
- Open or spread crushed rock material as a pioneer or thin ‘blind’ layer on top of the selected blasted waste rock base layer;
- Open, mix and spread selected materials as part of the wearing course construction; and
- Complete the final cut of a wearing course once compaction is complete.

A grader is used on operating roads for:

- Scarifying (shallow ripping) of in-situ softs or wearing course layers - in the case of the wearing course, deeper ripping is often part of a rehabilitation of the road where the ‘original’ wearing course is brought up to the surface to bring the road back to specification (trafficking and regular
blading often results in a build-up of fines in the upper 50mm of the wearing course over time, which causes the wearing course material to depart significantly from the original design specifications); and

- Routine road maintenance to blade (scrape) a road wearing course and redistribute the wearing course evenly across the road - for this work, highly skilled operators are required, often together with a laser- or GPS-guided levelling system to assist the operator in keeping his/her alignment and cross-fall, crown or camber, super-elevation, etc. Caterpillar’s Accugrade® and Opti-grade® are an example of these technologies.

Remember - if the road is not already damp, always water the wearing course lightly before you attempt to ‘grade’ or ‘blade’ the road. This will make the road easier to cut, provide a better finish and where significant cuts and drops are made, aid recompaction.

**Water car with 50-80klitre capacity and spray-bar**

The water car is very important, especially during compaction of the (non rocky) layerworks. It must apply water to the loose material being compacted, to bring the material to what is referred to as Optimum Moisture Content (OMC). This is the material moisture content associated with maximum density, and as will be seen later, maximum strength. The water car need not apply water to a base (if used) of selected blasted waste rock during compaction.

On finished roads, a nozzle spray-bar is a better solution to effective watering than is a plate or drop spray. Nozzles give finer coverage, less soaking and better watercart efficiency. Also - try to spray in ‘patches’ of 50m ‘on’ and 50m ‘off’ - this helps reduce potential damage to road from excessive water (especially on ramps; it also prevents excessively slippery conditions). Light watering improves water car spray productivity and reduces erosion of the road surface. However, as will be discussed later, water is inherently bad for a gravel road and, as a means of dust suppression - not that effective in some climatic regions. Also, using a pump with an integrated vehicle speed-delivery control to maintain approx. 0.5litres/m² road helps reduce overwatering on ramps and adopting an asset management and location system on water-cars is useful to manage spray coverages, optimise vehicle utilisation (spray-time) and as a means of reducing road network dust generation.

**Offset disc harrow plough**

An 8-10m wide offset disc harrow should be used for scarifying and mixing wearing course materials. A 4-wheel drive tractor tow unit (minimum 25kW per meter harrow width) is used with the plough. Where a mix of two or more materials is required to make a suitable wearing course, mixing is
very important and the offset disc is the quickest way to achieve this. As discussed earlier, when the grader has ripped the wearing course as part of the rehabilitation or regravelling work, the offset can also be used to breakdown the wearing course layer, prior to reshaping with the grader and recompacting.
Materials For Road Building

A road can be built above almost any (in-situ) material - but if that material is particularly weak (deforms easily when a load is applied), or the truck especially heavy, then a much thicker layerworks would be required to protect the in-situ material from the wheel load of the truck. Similarly, if the material we use to build the layerworks itself were weak - a thicker series of progressively stronger layers would also be required.

In a structural design specification, three broad materials types are generally considered:

- the in-situ (sub-grade) material on which the road is built, and if required, often the fill above in-situ;
- the sub-base and base layers (or as one, combined in a layer of selected blasted waste rock); and
- the wearing course layer, which is placed on top of the base layer.

What are the layer characteristics and what would make a good or poor material?

In-situ materials

These could be any of the following:

- soils;
- weathered overburden;
- loose blasted hard overburden; or
- solid hard overburden.

When planning a new road, the first task is to find out how hard or soft is the material we are going to build on.

A Dynamic Cone Penetrometer (DCP) and/or centre-line surveys and soil classification systems or materials sampling and laboratory testing can be used to establish the engineering characteristics and strength of the in-situ or sub-grade material on which the road is built.

There is not much choice in mining about what we build the road on. A road must connect two points, and often the shortest distance, or the most logical from a planning perspective, is the cheapest option. The mine block model often dictates where a road will be built, how much space it occupies, and what would be the effect on waste mining costs were a road to be planned in any location than the ‘minimum cost’ location.
If the in-situ is hard, solid overburden rock, then we usually have no problem. This is strong and does not need much protection from the wheel loads of the truck. We will still place selected fill on top of the in-situ to get the road profile and alignment correct - and critically, to allow water to drain through this layer and not the wearing course (the selected blasted waste rock fill is blocky and as such its strength not effected by water). Similarly, for a good strength blasted overburden, it is often only necessary to shape and compact the upper 300mm of the material before placing the wearing course.

If the in-situ is weathered overburden, it will be much softer, have typically higher clay content and thus require more protection - or a thicker sub-base and base layer(s) above it. Occasionally, the material is so soft that we have to remove it. This is because we want to reduce the thickness of the base, so we need a stronger in-situ on which to build. If the in-situ is soil or clay, or not trafficable (California Bearing Ratio (CBR)<2%) then this will be removed completely to a depth where stronger material is found. Also, if the material is very wet, the layer will also be removed and/or drainage installed, since without, it will make road building very expensive.

When a reasonably strong in-situ material is exposed, this can be ripped and compacted to provide an anvil for the compaction of the layers above. Without this anvil, compacting the layer above is difficult, time consuming and expensive. In both cases, the next type of material, the blasted rock base or fill replaces the material taken out. How much we use depends on the strength of the in-situ, applied wheel loads and design life of the road.
Sub-base and Base layers

Using a mechanistic structural design methodology, where a good quality (non-weathered) selected blasted overburden / waste is available, this material can be used as the combined base and sub-base. It is important that the blast block chosen as a source for this layer does not contain weathered rock, clay or soil, since for this layer we need blocky, hard material, with just a little (less than 20%) fine material. The largest block size is ideally 2/3 of the design layer thickness, which is usually between 200-300mm maximum. Any larger, and it is difficult to compact these boulders and they form a high spot in the layer surrounded by a ring of soft uncompact material. It also makes shaping the road difficult when large blocks protrude out of the layer. If such material is unavailable, then layers are constructed from selected excavated materials that offer a high strength on compaction. The choice of materials will depend on the quality, comparative cost and local availability. With these material types, stabilisation may be an option when used as a base layer.

Wearing course layer

This layer is made from a single or mix of materials. In the specifications introduced later, two recommended selection areas are given. When the wearing course parameters are determined, the result (of a single or mix of materials) should lie within these recommendations. If it does not, the specifications also give an indication of what ‘defects’ would normally occur as a result. The recommended limits for the selection of this material are established both in terms of performance and minimised road surface degeneration (degeneration equates to increased rolling resistance).

To achieve good layer strength, the material(s) for this layer must be carefully selected. Highly weathered rock will make for too much fine material, which will give very poor results and too soft a layer. Remember, we need hard, wear- and erosion-resistant materials for the large trucks to operate on. For this layer, a strength of greater than 80% CBR (California Bearing Ratio) is needed. This value is determined from laboratory tests of the material or by DCP Probing. If the mix is not correct, it can be too fine and will be slippery and dusty, or too unbound, when it will produce loose stones, corrugations, ravelling and, in both cases, rapidly increasing rolling resistance and operational risks once the road is trafficked.
DEVELOPING A HAUL ROAD CLASSIFICATION SYSTEM

Haul Road Classification

In a truck-based haulage system, the roads themselves should be considered an asset in a similar manner to the trucks that operate on them. Since not all roads comprising the mine network of roads fulfil the same function, and as a basis for cost-effective decision-making when developing a road design, improvement or maintenance management strategy, some basis of comparison is required - the basic haul road design specifications in this case.

To begin with, a road classification system should be developed, according to:

- traffic volume anticipated over life of road;
- vehicle type (largest anticipated truck fully laden on the road);
- permanence (service life of road); and
- performance (or service) level required.

as part of a mine-wide common framework or standard for the design and operation of the roads.

The classification system can be used as the starting point for specifying appropriate design guidelines for construction personnel, to enable them to easily determine what design and construction requirements are appropriate when constructing new, or evaluating and rehabilitating existing mine roads. Clearly, not all roads are ‘equal’ and for a cost effective approach, we need to tailor our design and management to apply more resources to high volume, long-term and high cost-impact road segments.

As was alluded to earlier, using rolling resistance (or it’s surrogate, fuel consumption) as a measure of cost-impact requires the haul road network to be divided into similar segments in terms of grade, traffic volumes, material types, etc. and then a small (+1%, +2%) change made to rolling resistance on each of these segments and results simulated using either OEM software or commercial equivalents (e.g. Talpac®, Runge Mining). Results will indicate which parts of the network are high cost-impact segments (in terms of increases in fuel consumption with increased rolling resistance, on the basis of total traffic volumes per segment) and require a higher road ‘classification’
than other segments. This basic analysis does not consider all the road-user costs, nor the cost of road maintenance since at this point we are interested in cost-sensitivity - not cost optimisation (the latter applies to haul road maintenance management).

This concept is illustrated above, which shows a model developed to estimate the fuel consumption index increase with road grade and rolling resistance (for a specific model of truck). The fuel consumption index represents the increase in fuel consumption from a base-case consumption when rolling resistance is 2.0% and grade is 0%. For example, a 359t GVM RDT has a base-case fuel consumption of about 40ml/s. The index increments for loading, speed and

<table>
<thead>
<tr>
<th>Rolling resistance (%)</th>
<th>Speed (km/h)</th>
<th>20</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case laden</td>
<td>0.49</td>
<td>0.74</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Base case unladen</td>
<td>0.43</td>
<td>0.65</td>
<td>0.86</td>
<td></td>
</tr>
</tbody>
</table>
grade increase are given in the illustration. Hence, the index increment for this laden truck travelling at 20 km/h up a 8.2% grade is (0.49 x 8.2) = 4.0, and at a rolling resistance of 2.1%, the fuel consumption increase from base case is (4.0 + 1.0) = 5.0 or about (5 x 40) = 200ml/s.

If rolling resistance now increases to 4.0%, the index increment is now 1.9 and fuel consumption rises to (4.0 + 1.9) x 40 = 236ml/s, equivalent to an 18% increase. Now for the same truck on a flat section of road, fuel consumption at 2.0% rolling resistance is approx. (0 + 2.3) = 2.3, or about (2.3 x 40) = 92ml/s. When rolling resistances increases to 4%, the increase in fuel consumption is about 84ml/s.

Hence, when road segment traffic volume is known, this data can be converted into a cost penalty associated with rolling resistance increases for each segment of haul road. The advantage of using OEM or similar simulation software is that the rate of production can also be analysed and if necessary, converted to an opportunity cost.

A typical classification (Category I to III roads) system is shown below, based on three categories of mine road. In this particular application, typical of a strip mine operation, the relatively long, flat haul to the spoil side of the pit (or ROM tip) resulted in the ex-pit roads having a higher cost-impact than the in-pit ramps, which were shorter and less highly trafficked.

<table>
<thead>
<tr>
<th>HAUL ROAD CATEGORY</th>
<th>Max daily traffic volume (kt hauled)</th>
<th>Traffic type (largest allowable vehicle)</th>
<th>Required performance index*</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CATEGORY I</td>
<td>&gt;100</td>
<td>376</td>
<td>3</td>
<td>Permanent high volume main hauling roads ex-pit from ramps to ROM tip or waste dumps. Operating life at least 10-20 years.</td>
</tr>
<tr>
<td>CATEGORY II</td>
<td>50 - 100</td>
<td>376</td>
<td>2</td>
<td>Semi-permanent medium- to high-volume ramp roads, or in-pit or waste dump N block roads ex-pit. Operating life 5-10 years.</td>
</tr>
<tr>
<td>CATEGORY III</td>
<td>&lt;50</td>
<td>288</td>
<td>1</td>
<td>Semi-permanent medium to low volume in-pit bench access or ex-pit waste dump sector roads. Operating life under 2 years.</td>
</tr>
</tbody>
</table>

Notes

# Performance index defined as;

1 Adequate in the short term, but fairly maintenance intensive once design life, planned traffic volume or truck GVM exceeded
2 Good with regular maintenance interventions over design life
3 Outstanding with low maintenance requirements over design life
For a typical open-pit operation, an example classification system is shown above. Note in this case that since the majority of the waste and ore hauled out of the pit travels on ramp to ROM or dump, it is these roads that were assessed ‘Category I’ roads since the cost impact of these types of road was extremely high and both productivity and cost could change dramatically if these roads were to under-perform (rapidly deteriorate with consequent increase in rolling resistance).

The typical classification systems and road categorisations shown here will be referred to again when we examine how design guidelines are developed for these various categories of road. Once the design categories have been determined, the key performance data for those truck types used to develop the categories of road, needs to be established. Truck manufacturers can supply this data. Together, these data form the basic input to the four design components previously discussed.

<table>
<thead>
<tr>
<th>HAUL ROAD CATEGORY</th>
<th>Max daily traffic volume (kt hauled)</th>
<th>Traffic type (largest allowable vehicle)</th>
<th>Required performance index</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CATEGORY I</td>
<td>&gt;150</td>
<td>391</td>
<td>3</td>
<td>Semi-permanent high volume main ramps to ROM Operating life at least 6-12 years.</td>
</tr>
<tr>
<td>CATEGORY II</td>
<td>100 - 150</td>
<td>391</td>
<td>3</td>
<td>Semi-permanent medium- to high-volume ramps to waste dumps K1, K2, K4. Operating life 2-5 years.</td>
</tr>
<tr>
<td>CATEGORY III</td>
<td>&lt;100</td>
<td>391</td>
<td>2</td>
<td>Transient medium to low volume bench access or ex-pit waste dump sector roads. Operating life under 1 year.</td>
</tr>
</tbody>
</table>

Notes
Performance index defined as:
1 Adequate in the short term, but fairly maintenance intensive once design life, planned traffic volume or truck GVM exceeded
2 Good with regular maintenance interventions over design life
3 Outstanding with low maintenance requirements over design life
Selecting and Using Appropriate Truck Data in Design Guidelines

Once the road categories have been determined, the key performance data for those truck types using the road needs to be established. Below are some of the key data to be considered, and how each piece of data is integrated into the four design components discussed.

**Gradeability**

- Engine, power train, transmission/wheel motor options and altitude corrections

The gradeability (refer propulsion or propulsion trolley line) of the truck will determine the optimum gradient of the haul road - but only where this can be accommodated from a mine planning perspective. Long flat hauls can be just as slow (in terms of total travel time) as short steep hauls, and there is an optimum grade (specified in terms of effective resistance (grade plus rolling resistance) which minimises overall (laden, against the grade) haul times. This optimum grade should be adopted for the basics of the geometric (ramp) design and careful note should be taken of its sensitivity to changes in rolling resistance. As mentioned previously, a good rule of thumb is that a 1% increase in rolling resistance on a 10% grade equates to about 10%-13% loss of speed.

Gradeability data will also indicate maximum speed of a truck under laden or unladen conditions and where braking is not the limiting speed factor, about 85% of this top speed should be used for design purposes - why slow-up
When you have purchased the engine power to actually complete a haul in a shorter time? Speed limits will always be necessary under certain operating circumstances in any haul road network, as will be discussed in the following sections concerning geometric design.

**Retarding**

- Braking system options

The brake performance of a truck is a key road design consideration especially when the truck is used in a laden-favourable (down-hill) grade configuration. For more conventional laden-unfavourable (up-hill) configurations, brake performance is only considered once the optimal grade has been specified and the impact of this decision analysed on unladen truck speed and road geometry. In this case, the effective total resistance is the ramp grade minus the rolling resistance.

With reference to the truck performance chart, with electric-drive trucks the braking effect is achieved through retard and mechanical braking. With mechanical drive trucks, the truck will descend a ramp in a gear that maintains engine rpm at the highest allowable level, without over revving the engine. If brake cooling oil overheats, speed is reduced by selecting next lower speed range. A typical brake performance chart for a mechanical drive truck is shown. When using this information for design purposes, select the appropriate grade distance chart that covers total downhill haul, not individual segments of the haul.

If the actual maximum safe speed of the truck under retard or braking is not exceeded, then speed limits may be necessary under certain circumstances, as will be discussed in the following sections concerning geometric design.
Dimensions

Several key dimensions are required - mostly to confirm the requirements for the geometric design component. These are typically:

- turning circle clearance diameter - used to specify minimum switchback radius (which should ideally be at least 150% of this minimum clearance value) and junction design considerations;

- height to drivers line of sight - used when assessing driver’s sight distance in vertical curves (especially sag curves) and comparing to minimum stopping distances; when stopping distance exceeds sight distance, speed limits are applied to bring stopping distance back within sight distance limitations;

- overall body length - for shorter RDT’s, normally not a key consideration in road design - but for BDT’s, the length of the unit needs to be considered in geometric design of curves and when tracking through junctions;

- overall body width - used to determine lane and roadway widths of the road; and

- Tyre size, used for outslope berm (windrow) design.

From the structural design perspective, we need to consider how the load is applied to the road - in terms of wheelbase and centerline spacing of the tyres, using:

- operating width,

- centreline front tyre width,

- centreline rear dual tyre width,

- type of tyre fitted and inflation pressure, and

- overall tyre width.

Weights

From the structural design perspective, we need to consider what load is applied to the road - in terms of:

- gross machine operating weight (GVM) – optionally using the empty vehicle mass (EVM) plus 1.2x payload (to accommodate the 10:10:20 loading limits of a truck) - this would be the limiting structural design data, used to determine the maximum wheel load applied to the road, in conjunction with:

- weight distribution across front and rear axles (laden and unladen);

- daily truck traffic volumes - based on tonnes moved and truck capacity, the data is used to determine the category of haul road required, and also to model the change in rolling resistance associated with wearing course deterioration.
GEOMETRIC DESIGN – GENERIC SPECIFICATIONS

Geometric Design - Introduction

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 allow. Any departure from the ideal specifications will result in reductions of both road and transport equipment performance. Considerable data already exists pertaining good engineering practice in geometric design, and many local standards apply, specifically developed for the local operating environment. Generic concepts are used as the basis of the design criteria developed here. 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 (85% of maximum design vehicle speed as an upper design speed), or, at the speed limit applied as dictated by the design itself. Ideally, geometric layout should allow the vehicles to operate up to the design 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 objective of connecting two points, and this objective is improved incrementally as the geometric specifications are applied and met.

Once the process of conceptual to final road design is completed, it has to be translated into construction activities in the field. This is where the skills and knowledge of construction staff becomes important.
Geometric Design - Vertical Alignment Issues

Stopping distance limits of truck

The manufacturer should confirm the distances required to bring the truck to a stop, following ISO 3450:1996 standards. The ISO 3450:1996 standard, which specifies braking systems' performance requirements and test procedures for earth-moving machinery and rubber-tyred machines is often used as a design standard by equipment manufacturers, to enable uniform assessment of the braking capability of earth-moving machinery operating on work sites or public roads. This ISO standard gives typically 114m stopping distance at 10% downgrade at 50km/h and 73m at 40km/h. Whilst this satisfies most mine ramp road designs where rear-dump trucks are used, care should be taken when using the ISO approach for articulated dump trucks (ADT). Steeper ramps are often used where ADT’s are employed, since they commonly have better hill climbing ability. With a ramp steeper than 10%, the ISO stopping distance would not necessarily apply. In general, and including driver reaction times and importantly, brake system activations times, practical retard unassisted (emergency) braking distances can be determined from the equation;

\[ \text{Stopping distance} = \frac{1}{2}gt^2 \sin \theta + v_o t + \left( \frac{(gt \sin \theta + v_o)^2}{2g(U_{\text{min}} - \sin \theta)} \right) \]

where;

- \( g \) = acceleration due to gravity (m/s²)
- \( t \) = driver reaction AND brake activation time (s)
- \( \theta \) = grade of road (degrees) positive downgrade
- \( U_{\text{min}} \) = coefficient of friction tyre-road, typically 0.3
- \( v_o \) = vehicle speed (m/s)

A reliable first estimate for stopping distance is based on ‘ideal’ braking and vehicle conditions (dry road, good skid resistance, etc.). When conditions under braking vary (wet roads, poor and slippery wearing course, spillage, etc.) a greater stopping distance would need to be considered. \( U_{\text{min}} \), the coefficient of tyre-road friction, is taken as 0.3 (wet, soft, muddy, rutted road surface) to 0.45 (partially-compacted dry gravel surface).
**Sight distances**

At least 150m is required - based on typical stopping distance requirements. On a curve or bend in the road, this could be difficult to achieve as shown in the diagram. When the road curves round a bench edge, to maintain sight distance a ‘layback’ (LB (m)) is used to keep the road away from the sight obstruction. The layback is found from consideration of the truck minimum stopping distance (SD (m) and curve radius R (m));

\[
LB = SD \left[ 1 - \cos \left( \frac{28.65R}{SD} \right) \right]
\]

Length (L (m)) of vertical curves can be determined from consideration of the height of the driver above the ground (h1(m)), an object of height (h2(m)) (usually 0.15m to represent a prostrate figure in the road), SD the minimum stopping distance (m) and ΔG the algebraic difference in grades (%);

**LB – Lay-back of curve from obstruction**
Unsafe – sight distance less than stopping distance

Required stopping distance

Sight distance

Vertical curve radius

Hazard

Safe – sight distance more than stopping distance

Required stopping distance

Sight distance

Vertical curve radius enlarged

Hazard

Unsafe – sight distance less than stopping distance

Required stopping distance

Sight distance

Hazard

Safe – sight distance more than stopping distance – layback or enlarged (horizontal) curve radius used

Mining Roads
Where stopping distance is greater than the length of a vertical curve, then;

\[ L = 2SD - \left( \frac{200(\sqrt{h_1} + \sqrt{h_2})^2}{\Delta G} \right) \]

Where stopping distance is less than the length of the curve;

\[ L = \left( \frac{\Delta G \cdot SD^2}{100(\sqrt{h_1} + \sqrt{h_2})^3} \right) \]

Any instance where sight distance is reduced below the stopping distance - this is DANGEROUS and speed limits should be applied OR sight distances increased.

**Optimal and maximum sustained grades**

Whilst maximum gradients may be limited by local regulations, ideally the gradient should be a smooth, even grade, not a combination of grades (or grade ‘breaks’). Laden trucks running against the grade work best at a total (effective) (i.e. grade + rolling resistance) value of about 8-11%. However, each truck engine and drive system combination has a characteristic ‘optimal grade curve’ and it is a good geometric design starting point to determine the optimal gradient for the selected truck in use at the mine. It should be noted that whilst travel times (laden) are sensitive to grades against the load, care should also be taken when selecting the grade, from the perspective of truck retard limitations on the unladen downward leg of the haul. This aspect becomes critical in the case of downgrade laden hauling when design retard capacity would be the limiting design criteria.

The optimal grade for a particular truck, engine and drive system option lies between the two extremes of;

- a long flat ramp - (truck is fast because effective resistance is low, but ramp is long - hence long travel times)
- a short steep ramp - (truck is slow because effective resistance is high - hence long travel times)
In this example, a simulation was used to determine optimum grade curve for a CAT 793C with 2-4% rolling resistance (RR) added to the grade resistance. The truck travel time is minimum at 11% grade (@2%RR) - but at the higher grades, the truck ‘works’ harder and will be more expensive to operate and life-cycle costs may be adversely affected. Also take note of the assumptions you use in the simulation work - especially length of ramp, curves (if any) and speed of truck on entry to the ramp. As RR increases, the optimum grade will decrease by the same amount.

At grades other than the optimal grade, it is also worth investigating the change of speed associated with changes in grade. As shown in the Figure, depending on the specific truck type and drive system adopted, it is not always a smooth exponential loss of speed with increasing grade (or increasing rolling resistance at a certain fixed grade).
Mining Roads

180t capacity, 317t GVM rear dump truck (mechanical drive) with 1416kW (1336kW @ flywheel) engine power, equivalent to 4.2kWt GVM.

194t capacity, 324t GVM rear dump truck (electric drive) with 1492kW (1389kW @ flywheel) engine power, equivalent to 4.27kWt GVM.
Horizontal (Longitudinal) Alignment Issues

**Width of road**

<table>
<thead>
<tr>
<th>Number of Lanes</th>
<th>Factor x Width of Largest Truck on Road</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

**Notes**

For switchbacks and other sharp curves and/or roads with high traffic volumes or limited visibility, a safe road width should be designed with an additional 0.5 x vehicle width.

A four-lane road is recommended where trolley-assist systems are in use.

Pavement (road) width should be sufficient for the required number of lanes. The associated safety shoulders are incorporated in the carriageway width and drainage features should be included in the formation width. The widest vehicles proposed determine the road width.

The diagram shows a lane width of 13m and a road width of 23m for a 6.5m wide RDT. At least 3.5 times the width of the truck should be used for the road width for bi-directional travel. This width excludes shoulders, berms and drains. Note that this accepted design methodology (3.5W) requires ‘sharing’ of the clearance allocation between lanes, which will require good driving skills - especially with larger haul trucks (to judge off-side clearance). Where traffic volumes are high or visibility limited, a safe road width would be 4W.
**Curvature and switchbacks**

Any curves or switchbacks should be designed with the maximum radius possible (generally >200m ideally) and be kept smooth and consistent. Changes in curve radii (compound curves) should be avoided. A larger curve radius allows a higher safe road speed and increased truck stability. Sharp curves or switchbacks will increase truck cycle times and haul cost as a result of rear dual tyre wear due to tyre slip and scrub especially with electric drive trucks.

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, as shown here. However, some truck models offer a ‘differential’, which allows for different dual tyre rotation speeds, which reduces the impact of tight curves on tyres. These enhancements improve the service life of the differential and dual wheel components where tight radius curves and switchbacks are numerous.

Minimum curve radius \( R \) (m) can be initially determined from:

\[
R = \frac{v_o^2 + U_{\text{min}} e}{127 e}
\]

Where;

- \( e \) = super-elevation applied (m/m width of road)
- \( U_{\text{min}} \) = coefficient of lateral friction tyre-road
- \( v_o \) = vehicle speed (km/h)

\( U_{\text{min}} \), the coefficient of lateral tyre-road friction, is usually taken as zero (wet, soft, muddy) to 0.20 (dry, compacted gravel surface). Where the pit layout requires a tighter radius than the minimum radius, speed limits need to be applied.
**Curve super-elevation (banking)**

Super-elevation refers to the amount of banking applied on the outside of a curve to allow the truck to run through the curve at speed. Ideally, the outward centrifugal force experienced by the truck should be balanced by the lateral (side) friction between tyres and road (taken as zero in the table below). Super-elevations should not exceed 5% - 7%, unless high-speed haulage is maintained and the possibility of sliding minimized.

<table>
<thead>
<tr>
<th>Curve Radius (m)</th>
<th>Speed (km/h) and super-elevation (m/m width of road)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>15  20  25  30  35  40  45  50  55</td>
</tr>
<tr>
<td>75</td>
<td>0.035 0.060 0.090</td>
</tr>
<tr>
<td>100</td>
<td>0.025 0.045 0.070 0.090</td>
</tr>
<tr>
<td>150</td>
<td>0.020 0.035 0.050 0.075 0.090</td>
</tr>
<tr>
<td>200</td>
<td>0.020 0.025 0.035 0.050 0.065 0.085</td>
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<tr>
<td>300</td>
<td>0.020 0.020 0.020 0.025 0.035 0.045 0.055 0.065 0.080</td>
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<tr>
<td>400</td>
<td>0.020 0.020 0.020 0.020 0.025 0.035 0.040 0.050 0.060</td>
</tr>
<tr>
<td>500</td>
<td>0.020 0.020 0.020 0.020 0.020 0.025 0.030 0.040 0.050</td>
</tr>
</tbody>
</table>

The Table shows typical super-elevation rates based on speed of vehicle and radius of curve. Elevation rates in the shaded blocks should only be applied as a combined super-elevation with a road (median) splitter berm used to separate slow and fast lanes of the road (each with its own speed-related super-elevation), due to the possible instability of slow-moving vehicles negotiating higher rates of super-elevation (especially where the road is wet). Where tighter curves are required or truck speed is higher on approach to the curve, a speed limit should be applied.

**Run-out (development of super-elevation)**

This refers to a section of haul road used to change from a normal cross-fall or camber into a super-elevated section. The change should be introduced gradually 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. Typical examples are shown here for the case of camber and cross-fall.
Run-out lengths vary with vehicle speed and total cross-fall change and can be estimated from the equation below where where CSx is the maximum change in cross-fall per 30m-road length and v₀ the speed of the truck (km/h).

Run-out is best incorporated in a mine road design by ‘eye’ rather than by calculation. Note that where the run-in or - out is at 0% (i.e. the road is ‘flat’) - there should be a slight grade ideally - to prevent water ponding on the road at this point. Generally, 0.02m/m/10m length of road is a good rule of thumb for the maximum run-out rate that should be used.

**Cross-slope, crown or camber**

A cross-fall, crown or camber is critical to the design and successful operation of mine roads. Applying a cross-fall, crown or camber ensures water does not gather on and penetrate into the road surface. Standing water on or in a road is extremely damaging and every attempt should be made to get water off the road as quickly as possible - but without inducing excessive erosion caused by high run-off velocities.

Poor crown or camber is shown here - all the water collects in the middle of the road - not the edges. Two options exist - either a cross-fall from one edge of the road to the other edge (USE WITH EXTREME CAUTION), or a crown (or camber), from the centre of the road to both sides of the road. Whatever option is adopted, at the point where the road edge and camber or
Special consideration must be given to determining when to use the maximum and minimum rates of cross-slope, crown or camber. Lower cross-slopes are applicable to relatively smooth, compact road surfaces that can rapidly dissipate surface water without the water penetrating into the road surface. In situations where the surface is relatively rough, a larger cross slope is advisable. On well-constructed gravel and crushed rock roads, with a longitudinal grade of more than 3%, the 2% criterion is preferable. Excessive slopes lead to erosion of the wearing course - which tends to be more prominent at the outer edges of the road (due to the higher run-off velocity) - and often coincident with the outer tyre path (wheel positions 1, 3 & 4) of the truck. Care should be taken with higher rates of cross-slope or crown in conjunction with steep longitudinal grades, the combination of which can cause a vehicle to slide – especially with a slower moving vehicle.
**Combined Alignment**

Here are a few tips when laying out a road with all the factors discussed above - to prevent some of the more common geometric design problems often encountered.

- **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 the mine plan dictates their use, make radius as large as possible, open road to 4x width of largest truck 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. Harsh braking before the curve will always generate excessive wearing course damage.

- **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 and 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.

- **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.

- **Avoid** staggered crossroads or other multiple road junctions. Preference should be given to 3-way over 4-way intersections. Re-align roads to provide for conventional cross road layouts and at any junction, 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, by reducing the centerline grade of the curve. The inside grade of the
curve should not exceed that of the ramp road. Using a transition spiral, and where pit room permits, set the inside gradient of the curve flatter than the ramp grade by 2-3% to compensate for increased curve rolling resistance.

**Safety Berms**

A ‘crest’ or road-edge berm /bund 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 inner (road) side of the safety berm should be preferably as steep as possible – 1.5V:1H -if needs dictate, by using an engineered or stabilised material. A steep (inner) berm face ensures better re-direction of the truck and less tendency to climb and topple. But in doing this, ensure stability and maintenance of height because a flat or low berm will also cause truck roll-over. For large haul trucks, the berm height should be at least 66% of the truck wheel diameter.

Truck GVM, speed 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 truck approach increases. Furthermore, large tyre 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.

Where a median (centre) berm is used to split two lanes of traffic, or in the vicinity of junctions (splitter islands), the same design principles should be applied. Consideration also needs to be given to both the function of the median or centre berm and the implications in using such. In addition to the cost of construction and the additional formation width that is required (which could impact stripping ratios), how to accommodate grader maintenance, broken-down vehicles, etc. and the impact on drainage should all be additional considerations.
Ditches and Drainage

A well-designed drainage system is critical for optimum mine haul road performance. Water on the road or in the road layers will quickly lead to poor road conditions. As part of the haul road geometric design process, contours in the vicinity of the proposed road should be examined prior to construction to identify areas of potential ponding and the location of culverts, etc.

The drains at the edge of the road should be designed to lead the water off the road without causing erosion. Do not cut drains into the base layer - ensure drains are ‘lined’ with compacted material, thereby preventing water from seeping into the underlying layers.

Poor drainage led to collapse of this road near the bench wall - this was a low-spot and water could go nowhere - except seep into the road layerworks. Ideally, either a culvert could have been installed here, or water lead across the road by using a sag curve and cross-fall to outslope combination at this point.

Also take care not to leave windrows of wearing course (after grading the road) along the edges of the road - they will also prevent water from draining off the road surface. Make sure that after blading a road, windrows (and if appropriate, safety berms too) are cut through at regular intervals to assist drainage. If circumstances permit, consider blading over-wet wearing course to the centre of the road, not the sides of the road. Windrows of wet material at the side of the road cause ponding of water – and also pick-up spillage which is a problem when opening the wearing course and spreading back onto the haul road.

For drainage, V ditches are recommended for nearly all applications, owing to the relative ease of design, construction, and maintenance. The ditch cross slope or shoulder adjacent to the haul road should be 4H:1V, or flatter, except in extreme restrictive conditions. In no case should it exceed a 2H:1V slope. The outside ditch slope will vary with the material encountered. In rock it may approach a vertical slope; in less consolidated material, a 2H:1V slope or flatter. In a cut/fill section, use a cross-slope toward the cut side and run drainage in a single ditch. In a total cut or total fill section; carry drainage on both sides with crown or camber from the road centerline. Ditch lining is a function of road grade and in-situ material characteristics.
■ At 0% to 4% grade, the ditch may be constructed without benefit of a liner except in extremely erodible material such as sand, or easily weathered shale and silts.

■ At grades over 5%, the lining should consist of coarse, crushed waste rock placed evenly on both sides to a height no less than 0.3m above the maximum depth.

Ditches must be designed to adequately handle expected runoff flows under various slope conditions. The primary consideration is the amount of water that will be intercepted by the ditch during a rainstorm. Typically, a 10 year, 24-hour storm chart should govern the design. Culvert sections are used to conduct run-off water from drainage ditches under the haul road. If buried piping is used, set to 3-4% fall and use smooth-wall concrete pipes in conjunction with a drop-box culvert of a size suitable to enable it to be cleaned with a small backhoe excavator. At all culvert inlets, a protective encasement or “headwall” consisting of a stable non-erodible material should be provided.

Typical culvert units are either portal and rectangular precast concrete culvert units or precast concrete pipe culvert units. Depth of cover over the culvert pipe is determined by the type of culvert in relation to the vehicles that will use the road. A minimum cover of 1000mm over the pipe is required in most cases. All prefabricated culverts should be constructed under trenched conditions once the road has been constructed. Concrete pipe culverts are laid on a layer of fine granular material, 75 mm thick, after the bottom of the excavation has been shaped to conform to the lower part of the pipe. Where rock, shale or other hard material is encountered on the bottom of excavations, culverts should be placed on an equalizing bed of sand or gravel. Once placed, the culvert trench is backfilled and compacted.
STRUCTURAL DESIGN – GENERIC SPECIFICATIONS

Introduction to Structural Design of Haul Roads

Haul road structural design concerns the ability of the road to carry the imposed loads without the need for excessive maintenance or rehabilitation. Haul roads deteriorate with time due to the interactive effect of traffic load and specific subgrade and in-situ material strengths and structural thicknesses.

The CBR structural design method 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 often appropriate.

When a selected (blasted) waste rock layer is located immediately 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.

Critical in any structural design are:

- the compaction of the in-situ and the compaction and thickness of the layerworks or (selected) blasted waste rock layer as a base; and

- the layer thicknesses (or ‘cover’) selected -. If the layer is not thick enough (too little ‘cover’) or not well compacted during construction, then it will compact when trucks drive on the road, leading to very poor conditions and large depressions/rutting in the road.

When these critical design requirements are overlooked, poor road performance will result. In the Figure, poor structural design is due to collapse of layers below the road as a
result of the weak in-situ (soft weathered spoils). Here, either structural design
(‘cover’ above in-situ spoils) and/or compaction of in-situ and/or layerworks
were deficient. Rutting and large depressions of 0.4m depth are seen.
Generic Construction Specifications

The Figure shows a blasted selected waste rock base layer, placed at design thickness above the (red) in-situ. If the material comprising the base layer is not to the correct specification, or not placed and compacted correctly, the road will not perform well. In the figure, you can see the hard, 'blocky' type of waste rock that should be used, and it's ideal size - maximum block size about 2/3rds of the layer thickness.

Compaction is one of the critical processes in mine road construction. It is needed to achieve high quality and uniformity of material in the layerworks, which in turn better ensures long-lasting performance. Achieving these uniformly is key.

Construction specifications state that the layer (placed in lifts not exceeding about 200mm for vibratory roller compaction and 500mm for an impact roller) should be compacted ‘until negligible movement seen under the roller’ - this means that when the roller is driven over the layer, you should not see any ‘tracks’ under the roller - everything is now well compacted (or alternatively, ‘intelligent compaction’ systems may be used to identify when layer compaction is complete, for instance Caterpillar’s Compaction Meter Value (CMV®) system or Bomag’s Evibe® method). For an impact roller, generally speaking, 10-15 passes should be sufficient per lift. In this picture, you can still see ‘tracks’ of the roller - hence compaction of the layer is not yet complete.

If using selected blasted waste rock for the combined base and sub-base layers, where possible, design a blast specifically for road layerworks. Increase powder factor and/ or reduce burden and spacing to give maximum fragment sizes of about 200-300mm(do not try to bury oversize in the road - they will result in poor local compaction) Dig and dump the material either directly in the road, or stockpile it for later use.
Structural Design Methodologies

California Bearing Ratio (CBR) Cover-curve Design Method

The California Bearing Ratio (CBR) cover-curve design method developed by Kaufmann and Ault (USBM) 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 (generally the smaller truck wheel loads and Category III roads only). However, the method does not account for pavement life – or how much truck traffic the road is expected to carry – hence a short temporary road is designed with the same parameters as a life of mine road. Although a potential deficiency, a ten-fold increase in traffic volumes may only require a 10%-20% increase in pavement thickness, when compared with airfield design techniques used by the USACE.

The chart on the following page shows an updated version of the USBM CBR design charts, 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) and the American
Association of State Highway and Transportation Officials’ (AASHTO) systems. Total pavement thickness is used in this chart as opposed to the original sub-base thickness criteria.
The following equation can alternatively be used to estimate the layer thickness \( Z_{CBR} \) required for a material of California Bearing Ratio (CBR %);

\[
Z_{CBR} = \frac{9.81 t_w}{P} \left[ 0.104 + 0.331 e^{-\left(0.029 t_w \right)} \right] \left[ 2 \times 10^{-5} \left( \frac{\text{CBR}}{P} \right) + \left( \frac{\text{CBR}}{P} \right)^{-3.31} \right]
\]

Where \( t_w \) is the truck wheel load (metric tons), \( P \) is tyre pressure (kPa) and CBR is the California Bearing Ratio of the material (%).

Originally, the wheel load was increased by 20% to replicate the effects of 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). The following equation can be used to estimate the cover \( Z_{ESWL} \) more reliably as;

\[
Z_{ESWL} = Z_{CBR} + 0.184 + \left[ 0.086 \text{CBR} + \frac{17.76 \text{CBR}}{t_w} \right]^{-1}
\]

In using this technique, consider the ‘cover’ required for a 320t GVM haul truck with a 55t wheel load. Using an ESWL approximation of 1.2xwheel load, if the sub-grade CBR is 5%, the pavement thickness required is 1400mm. If a sub-base of CBR=15% were placed above this, pavement cover is now 500mm so \((1400-500) = 900\)mm layer thickness is required. Placing a base of CBR=35% results in a layer thickness of 375mm, following which a 125mm layer of CBR>80% wearing course is applied. Ideally, a yet harder material is required, but a wearing course of CBR>80% is generally suitable and would for design purposes be specified to 200mm depth from surface.

Using the equations presented previously for \( Z_{ESWL} \) gives 1790mm cover, and layer thicknesses of 950mm, 430mm and \((260+150)\)mm for each layer respectively.

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.
Using a mechanistic design methodology, the specification of the layer thicknesses and compaction is based on limiting load-induced strains in the softer in-situ to below certain critical values. These values are associated with the category of road being designed, truck size, performance requirements and road operating life. The higher the traffic wheel loads and volumes (kt/day) and the longer the operating life and associated performance requirements are of the road, the lower is this critical strain value. This data is then used to determine the thickness of the blasted rock layer to be placed on top of the in-situ or fill such that the road will perform satisfactorily over its design life.

As discussed earlier, if a road classification system is developed, the design categories established will reflect these critical strain values.

A mechanistic design is based on a theoretical linear-elastic multi-layer system model of road layers. A limiting design criterion of vertical compressive strains in the sub-grade or in-situ is then used to assess the haul road under the specific loading conditions, thereby determining the adequacy of the structural design. 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. Data from a road classification and categorisation exercise, as discussed earlier, can be used to assist in selecting a limiting strain value, according to the category of road to be built and the associated operating life and traffic volumes, as shown in the chart. 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.

To determine the layer response to an applied load, a layered elastic model should be used to represent the various haul road layers in the design. Software is available which can be used to solve multi-layer problems in road design, including ELSYM5, MePADS, FLEA and CIRCLYS. Irrespective of the solution software used, the approach is similar.

The effective modulus of elasticity (E<sub>eff</sub>) (resilient modulus) and Poisson’s ratio (ν, typically 0.35) define the layerworks material properties required for computing the vertical strains (ε) in the road. In addition to the material properties, a layer thickness (200mm) is also specified for the wearing course. By varying the thickness of the selected blasted waste rock 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 (in-pit blasted rock) or in-situ (ex-pit softs or weathered overburden). 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, and the lowest pavement layer to be infinite in depth.

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 tyre pressure, the contact stress is calculated. The Figure summarizes the layered elastic model and data requirements.

The strains induced in a pavement are a function of the effective elastic (resilient) modulus values assigned to each layer in the structure. In order to facilitate mechanistic design of mine haul roads, some indication of applicable modulus values is required. The Table recommends modulus value correlations to USCS and AASHTO classification systems. To facilitate the choice of suitable modulus values for in-situ materials, the associated range of CBR values derived in the field from Dynamic Cone Penetrometer (DCP) probing, are also given.
The following equation can also be used in conjunction with layer CBR values to determine modulus values ($E_{\text{eff}}$, MPa), but in either case, 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.

$$E_{\text{eff}} = 17.63 CBR^{0.64}$$

The modulus value adopted for the selected blasted waste rock base layer is typically 1500-3000MPa. This value is derived from consideration of a cement-stabilized layer in its pre-cracked (large intact blocks with some shrinkage cracks) state, which corresponds closely to a well-compacted waste rock layer. Where compaction is poor, or lifts excessive, this value should be reduced to 1500-2000MPa.

**DCP Evaluation of In-situ Materials**

Since each mine road design situation varies, it is necessary to gather data concerning the strength of the in-situ material and layerworks material before a design is determined. This can be done both by Dynamic Cone Penetrometer (DCP) probing and laboratory tests of typical road building material, to determine its load bearing capacity or California Bearing Ratio (CBR(%)), or $E_{\text{eff}}$ resilient modulus following one or other material classification system. A DCP field test can be used to assess CBR or strength of a road layer and is additionally useful for:

- evaluating where any problems (soft spots) could exist in a road once it is made; and
- evaluating the ‘as-built’ strength achieved in the compacted in-situ (if applicable) and especially the wearing course layer of a completed road - from 0mm-200mm depth.

A DCP is used to assess the strength of the layers in the road (and the in-situ in some cases). It relates depth into the pavement or in-situ with strength at that point. The DCP is hammered into the road and every 5 hammer blows, a depth reading is taken. This reading is then subtracted from the previous depth reading to give the penetration per 5 blows, over the depth increment. The DCP design specifications are shown in the Figure, the ‘hammer’ shown as item 2.

Using the graphs illustrated, for every 5-blow increment, first determine the CBR value at each depth, and then secondly plot this CBR value on the depth/CBR graph, an example of which is given on the next page.
1. Handle
2. Hammer (8kg)
3. Hammer shaft
   575mm drop height
4. Coupling
5. Hand guard
6. Clamp ring
7. Standard shaft
8. 1m rule
9. 60° cone

Dynamic Cone Penetrometer
Pavement CBR(%) values from penetration (mm for every 5 blows)
Design Charts for Common Haul Trucks

The design charts given on the next pages are based on a fully laden haul truck, operating at the manufacturers maximum recommended Gross Vehicle Mass (GVM, tons) with standard recommended (radial) tyres, inflated to 800kPa.

The road design is assumed to incorporate 200mm of wearing course with a CBR>80%, a good-quality well-compacted selected blasted waste rock base layer (as discussed above), built on in-situ material with the indicated E-modulus shown on the charts. The in-situ material depth is limited to 3000mm, where after a stiffer layer is assumed to exist (either soft-rock or saturated material).

The charts give the base (rock) layer thickness required for a Category I, II and III haul road, for the particular model of truck. If any of the above parameters do not apply to the design case, then a special analysis is required to accommodate the requirements of the application.
FUNCTIONAL DESIGN AND SHEETING PERFORMANCE SPECIFICATIONS

Introduction to Functional Design

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, sheeting (or road surfacing) materials. Poor functional performance is manifest as poor ride quality, excessive dust, increased tyre wear and damage, and an accompanying loss of productivity due to rolling resistance increase associated with surface deterioration (or ‘defects’). The result of these effects is seen as an increase in overall vehicle operating and maintenance costs.

The functional design specifications are concerned with the wearing course (or sheeting) layer. The material used must meet specification and be constructed (critically here, compacted) correctly. If not, the road will perform poorly and be maintenance intensive - regular grading or scraping of the road will be required because the wearing course is either too soft, too loose ( friable or ravelling ), too dusty or too slippery (when wet especially, but also when dry due to the presence of loose or ‘ unbound ’ material on the surface). These problems are referred to as road condition ‘ defects ’ and any functional design specification is aimed at reducing these defects - and as will be seen, thereby reducing rolling resistance.

Sheeting is tipped on top of the base or selected blasted waste rock layer. A wheel dozer or grader will then open the material and spread it evenly over the road before it is compacted. The camber ( crown ) of the road has already been established in the base layer - this means that the wearing course layer can be a constant 200mm thickness across the full width of the road, including the side or table drains, which form part of the construction width.

Note also that the wearing course layer is significantly weaker than a selected blasted waste rock base layer; hence we do not want an excessively thick layer of this material on top of the road. Its primary job is that of providing a safe, vehicle friendly and low-cost running surface, free of excessive defects. Strengthening a poorly built road requires increasing base and/or sub-base layer thicknesses and strength, not simply increasing wearing course layer thickness alone – this layer contributes to the overall structural strength of the road but modification will not solve inadequate cover issues.
Wearing Course Material Sourcing and Preparation

The material specifications will be discussed shortly - however, it is easy to ‘recognise’ a good wearing course material (but you also have to test any material you propose to use to make sure that it meets specifications).

On the left, this is probably a good mix of crushed rock to use, everything smaller than 40mm in size and not too much fine material (less than 20% passing (finer than or ‘minus’ 0.425mm). Be wary of smooth round alluvial aggregate in the mix - this will not easily interlock and will eventually ravel out of the wearing course.

On the lower left is a material that will not form a good wearing course. It can be seen that there is no fine binding material in the mix - hence when compaction is attempted, the material will not ‘bed-down’. It is also not suitable for a base layer either. Although there are no fines (good from the perspective of a base layer material), there is very little variation on size in the mix and it will not compact well and interlock (a problem compounded by the smooth alluvial aggregate in the material).

Often, where no suitable wearing course material or mix of materials can be found from borrow-pits in and around the mine, a small jaw crusher can be used to prepare blasted rock as a wearing course aggregate, often in a mix of one or more other materials to form the final product. This is also useful for creating a fine aggregate from waste rock to be placed as a dressing on the loading floor and tip head approach, to reduce tyre damage and lift the road out of water/spillage.
in these areas (and, once you are producing this material, very often it can be used for many other purposes in and about the mine too). Remember - the haul road runs everywhere a haul truck runs – loading floor, ROM or waste tip head areas should also be considered part of the network of haul roads. Even ‘short-term’ poorly prepared roads will contribute to ‘long-term’ damage to the mine trucks.

The following figures show one particular application where a suitable material was sourced in-pit, blasted to produce road-building material and dumped on surface. The first Figure is the source material for base layer construction, the second some of this material is loaded into a jaw crusher to produce a minus 40mm product used in the wearing course, as shown in the last Figure.
Wearing Course Material Selection

The functional design of a haul road is the process of selecting the most appropriate wearing course (or sheeting) material or mix of materials, typically natural gravel or crushed stone and gravel mixtures that are commensurate with safety, operational, environmental and economic considerations. The most common wearing course material for haul roads remains compacted gravel or gravel and crushed stone mixtures. In addition to their 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 maintained at relatively low cost. As with structural designs, if local mine material can be used for construction, the costs are all the more favourable. This cost advantage is, however, not apparent in the long term if the characteristics of the wearing course material result in sub-optimal functional performance.

An ideal wearing course for mine haul road construction should meet the following requirements:

■ the ability to provide a safe and vehicle friendly ride without the need for excessive maintenance;
■ adequate trafficability under wet and dry conditions;
■ the ability to shed water without excessive erosion;
■ resistance to the abrasive action of traffic;
■ freedom from excessive dust in dry weather;
■ freedom from excessive slipperiness in wet weather; and
■ low cost and ease of maintenance.

The defects most commonly associated with mine haul roads, in order of decreasing impact on hauling performance are typically:

■ Skid resistance - wet,
■ Skid resistance - dry,
■ Dustiness,
■ Loose material,
■ Corrugations,
■ Stoniness - loose,
■ Potholes,
■ Rutting,
■ Stoniness - fixed,
■ Cracks - slip, longitudinal, and crocodile.
Climate is also a consideration in material selection; where a wet climate is encountered, fines should be restricted to less than 10% to prevent muddy, slippery conditions when wet. On the other hand, in drier climates, fines should exceed 5% to prevent ravelling or loosening of the wearing course aggregates.

By examining which wearing course material property parameters lead to these defects, a specification has been developed for wearing course materials selection. The specifications are based on an assessment of wearing course material shrinkage product (Sp) and grading coefficient (Gc), defined below. Note that this specification is based on AASHTO sieve sizes and if AS1289 sieve sizes are used to classify a wearing course material, corrections will have to be applied to calculate the equivalent AASHTO sieve sizes.

\[
\begin{align*}
Sp &= LS \times P425 \\
Gc &= \frac{(P265 - P2) \times P475}{100}
\end{align*}
\]

where;

\begin{align*}
LS &= \text{Bar linear shrinkage} \\
P425 &= \text{Percent wearing course sample passing 0,425mm sieve} \\
P265 &= \text{Percent wearing course sample passing 26,5mm sieve} \\
P2 &= \text{Percent wearing course sample passing 2mm sieve} \\
P475 &= \text{Percent wearing course sample passing 4,75mm sieve}
\end{align*}

A suitable wearing course material can be determined from the selection chart shown here, in terms of the two parameters that describe the material; the grading coefficient (Gc) and shrinkage product (Sp). 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 defines the focus point of the specifications to 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. Area 2 specifications would suit a Category II or III road, from a performance perspective, whilst Category I or II roads would ideally have a wearing course that falls in Area 1. If the wearing course falls outside the specifications - the chart shows you what sort of problems (defects) you can expect. When the wearing course material or mix of materials is sub-optimal, ‘functional’ defects rapidly form on the road and this creates safety and performance problems for the mine.

If the only materials available for wearing course selection lie outside the parameters limits, a mixture of those materials can be evaluated using the above guidelines. The proposed mix ratio can be used to define a new ‘mixed’ material specification proportional to the mix ratio, from which Gc and Sp can be determined. In a similar fashion, an existing haul road wearing course can be successfully rehabilitated by adding an appropriate material to restore the mix to specification. The specifications should also be evaluated in the light of other material property limits identified as important in functional performance but not directly assessed in the selection chart. The Table below presents a summary of these property limits, together with the type of road defects most often associated with departures from the recommended parameter ranges.
The advantage of this approach to material specification is that it enables a wearing course to be selected from two or more apparently unsuitable materials that, on their own, would not meet minimum specifications.
The typical test results from two possible wearing course materials are shown here, and it can be seen how, when the materials are used on their own, they would be unsuitable, but when mixed in a specific proportion with the existing (also unsuitable) wearing course, they would make an ideal wearing course. The data was used to determine the new wearing course material mix shown in the diagram above. Note that the data is not generic and would obviously differ between mines.
Using the specifications’ guidelines, a mix consisting of 60% by mass crushed waste, 20% existing wearing course from the current road and 20% plant discard was found to meet the specifications and the road was rehabilitated (adding other materials into the existing wearing course to improve its performance). In all cases, a maximum wearing course layer thickness of 200mm is recommended, with a (4-day soaked) CBR $\geq 80\%$.

The wearing course parameters mentioned in the selection guidelines are determined from typical ‘road indicator’ civil engineering laboratory tests, similar to those shown on the next page. Typically, these tests will cover:

- screen analysis to -0.075mm;
- constants (Atterberg limits and bar linear shrinkage);
- mod AASHTO or (equivalent local compaction specifications) at various compactive efforts; and
- optimum moisture content (OMC), maximum dry density.
<table>
<thead>
<tr>
<th>SAMPLE DESCRIPTION</th>
<th>DARK BROWN SLAG GRAVEL</th>
<th>DARK BROWN SLAG GRAVEL</th>
<th>LIGHT BROWN DOLERITE SANDY GRAVEL</th>
</tr>
</thead>
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<tr>
<td>Sample Number</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Sample Position</td>
<td></td>
<td></td>
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<tr>
<td>Sample Depth (mm)</td>
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<tr>
<td>Material Description</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Max size of boulder (mm)</td>
<td>130</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>SCREEN ANALYSIS (% PASS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75.00 mm</td>
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<td>100</td>
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<td>63.00 mm</td>
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<td>93</td>
</tr>
<tr>
<td>53.00 mm</td>
<td>77</td>
<td>100</td>
<td>85</td>
</tr>
<tr>
<td>37.50 mm</td>
<td>73</td>
<td>100</td>
<td>78</td>
</tr>
<tr>
<td>26.50 mm</td>
<td>60</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>19.00 mm</td>
<td>45</td>
<td>89</td>
<td>61</td>
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<tr>
<td>13.20 mm</td>
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<td>87</td>
<td>55</td>
</tr>
<tr>
<td>4.750 mm</td>
<td>37</td>
<td>61</td>
<td>45</td>
</tr>
<tr>
<td>2.000 mm</td>
<td>32</td>
<td>37</td>
<td>39</td>
</tr>
<tr>
<td>0.425 mm</td>
<td>27</td>
<td>17</td>
<td>34</td>
</tr>
<tr>
<td>0.075 mm</td>
<td>14</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>SOIL MORTAR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarse Sand</td>
<td>2.000-0.425</td>
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<td>55</td>
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<tr>
<td>Coarse Fine Sd</td>
<td>0.425-0.250</td>
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<tr>
<td>Medium Fine Sd</td>
<td>0.250-0.150</td>
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<tr>
<td>Fine Fine Sand</td>
<td>0.150-0.075</td>
<td>32</td>
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<tr>
<td>Material</td>
<td>&lt;0.075</td>
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<td>CONSTANTS</td>
<td></td>
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<tr>
<td>Grading Modulus</td>
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<td>2.38</td>
<td>2.03</td>
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<td>Liquid Limit</td>
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<td></td>
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<tr>
<td>Plasticity Index</td>
<td>SP</td>
<td>SP</td>
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<tr>
<td>Linear Shrinkage (%)</td>
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<td>0.5</td>
<td>0.5</td>
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<td>Sand Equivalent</td>
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<tr>
<td>Classification - TRB</td>
<td></td>
<td>A-1-a (0)</td>
<td>A-1-a (0)</td>
</tr>
<tr>
<td>Classification - COLTO</td>
<td></td>
<td>G6</td>
<td>G4</td>
</tr>
<tr>
<td>CBR / UCS VALUES</td>
<td>CBR</td>
<td>CBR</td>
<td>CBR</td>
</tr>
<tr>
<td>MOD. AASHTO</td>
<td></td>
<td></td>
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<tr>
<td>Max Dry Density (kg/m³)</td>
<td>2869</td>
<td>2620</td>
<td>2582</td>
</tr>
<tr>
<td>Optimum Moisture Cont (%)</td>
<td>6.7</td>
<td>4.5</td>
<td>9.5</td>
</tr>
<tr>
<td>Moulding Moisture Cont (%)</td>
<td>7.0</td>
<td>4.4</td>
<td>9.1</td>
</tr>
<tr>
<td>Dry Density (kg/m³)</td>
<td>2864</td>
<td>2567</td>
<td>2584</td>
</tr>
<tr>
<td>% of Max Dry Density</td>
<td>99.8</td>
<td>98.0</td>
<td>100.1</td>
</tr>
<tr>
<td>100% Mod CBR/UCS</td>
<td>67</td>
<td>112</td>
<td>26</td>
</tr>
<tr>
<td>% Swell</td>
<td>0.1</td>
<td>0.0</td>
<td>0.4</td>
</tr>
<tr>
<td>NRB</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry Density (kg/m³)</td>
<td>2789</td>
<td>2436</td>
<td>2517</td>
</tr>
<tr>
<td>% of Max Dry Density</td>
<td>98.5</td>
<td>93.0</td>
<td>97.5</td>
</tr>
<tr>
<td>100% NRB CBR/UCS</td>
<td>34</td>
<td>85</td>
<td>20</td>
</tr>
<tr>
<td>% Swell</td>
<td>0.1</td>
<td>0.0</td>
<td>0.8</td>
</tr>
<tr>
<td>PROCTOR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry Density (kg/m³)</td>
<td>2745</td>
<td>2404</td>
<td>2465</td>
</tr>
<tr>
<td>% of Max Dry Density</td>
<td>95.0</td>
<td>91.8</td>
<td>95.5</td>
</tr>
<tr>
<td>100% Proc CBR/UCS</td>
<td>25</td>
<td>53</td>
<td>16</td>
</tr>
<tr>
<td>% Swell</td>
<td>0.0</td>
<td>0.0</td>
<td>0.7</td>
</tr>
<tr>
<td>CBR / UCS VALUES</td>
<td>100% Mod AASHTO</td>
<td>69</td>
<td>140</td>
</tr>
<tr>
<td>98% Mod AASHTO</td>
<td>46</td>
<td>112</td>
<td>21</td>
</tr>
<tr>
<td>97% Mod AASHTO</td>
<td>37</td>
<td>101</td>
<td>19</td>
</tr>
<tr>
<td>95% Mod AASHTO</td>
<td>25</td>
<td>81</td>
<td>15</td>
</tr>
<tr>
<td>93% Mod AASHTO</td>
<td>17</td>
<td>65</td>
<td>12</td>
</tr>
<tr>
<td>90% Mod AASHTO</td>
<td>9</td>
<td>40</td>
<td>9</td>
</tr>
</tbody>
</table>
Besides assessing the material used in the wearing course, it is also important that the wearing course is built to specification. Two concepts are important here, the CBR or strength achieved and the amount of moisture needed to add to the material to get the specified strength.
Placement and Compaction

**Moisture content and compaction**

Previously, it was noted that when compacting the base layer (if the material is selected blasted waste rock), this should be done dry (no water added to the material). In the case of the wearing course (and other layerworks), the material(s) used here possess optimum densities that ensure adequate support, stability, and strength. Adding water to the material enables fine particles to move past one another during the application of the compacting forces. As the wearing course compacts, the voids are reduced and this causes the dry density to increase to a point, but then fall because achievable compaction is limited by the volume occupied by pore water (the zero air void line (ZAV)). There is not time during compaction for water to be squeezed out. When the wearing course or other constructed layer approaches the ZAV line (which gives the maximum dry density for a given moisture content), a maximum dry density is reached and the moisture content at this maximum is called the optimum moisture content (OMC).
Increasing compactive effort enables greater dry densities to be achieved at lower OMCs. The effect of increasing compactive energy can be seen in the illustration. When moisture content is larger than OMC, larger compaction equipment will have only a small effect on increasing dry densities. For this reason it is important to have good control over moisture content during compaction in the field.

The site procedure is to specify that the layer or wearing course must be compacted to some pre-determined dry density. This specification is usually that a certain percentage of the maximum dry density, as found from a laboratory test (e.g. Mod AASHTO) must be achieved. For example, field densities must be greater than 98% of the maximum dry density as determined from the Mod AASHTO Compaction Test (98% Mod AASHTO MDD). It is then up to the contractor to select machinery, the thickness of each lift (layer of material added until specified layer thickness and strength is achieved) and to control moisture contents in order to achieve the specified degree of compaction. It is usual to do some trial compaction tests to determine the number of passes and the amount of water to be added to achieve specification. As an alternative, Intelligent Compaction, using vibratory rollers equipped with an in-situ measurement system and feedback control, can be used. GPS based mapping is included, together with reporting software. By combining measurement, reporting and control systems, the use of these rollers allows for real-time corrections in the compaction process. The rollers also maintain a record that includes number of roller passes, roller-generated material stiffness measurements, and precise location of the roller. It is generally best to try and keep passes to a minimum. Because of the heavy trucks using the road, it is better to construct ‘dry’ of optimum (slightly to the left of OMC in the diagram), rather than at optimum or above.

Method specification notes

The method specification for placement of the wearing course depends on whether the haul road is being built from new, or being rehabilitated (where material is mixed with the existing wearing course to bring it back to specification). For rehabilitation, the existing wearing course layer should be ripped and scarified and any large lumps of compacted material broken down to a maximum size of 1/3 of the compacted layer thickness. During the processing, the scarified layer should be ploughed or bladed to bring large lumps to the surface. An offset disc harrow can be used for this purpose. For both new and rehabilitated roads, the material to be mixed should be spot dumped, opened (and mixed with the existing wearing course if rehabilitation is done). Placement of the wearing course should proceed in two lifts of 100mm, each compacted to 98% Maximum Dry Density to give a minimum CBR of 80% using between 4-8 passes of a vibratory roller and with either moisture content at or slightly dry of optimum.
The Selection and Application of Dust Palliatives

Water-spraying of the haul road is the most common means of dust suppression. However, it is not necessarily the most cost-effective means of reducing dust emissions, especially where water is a scarce resource and/or evaporation rates are high. Excessive watering can lead to erosion of the wearing course, and where the material Sp is high, small (3-7cm diameter) potholes are likely to form. This is not problematic per se, but they will induce more rapid wearing course deterioration. More effective watering can be achieved by using a spray-bar and nozzles mounted close to the road surface, for a more even, lighter watering of the road (0.5litres/m²) than would be achieved with a drop-plate arrangement. Results can be further improved by:

- integrating truck speed with water delivery rate, to prevent over-watering ramps, etc; and
- using a 50m on 50m off (intermittent) spray pattern on the roads and allowing truck tyres to carry water over to the dry section. This also improves safety on ramp segments, especially on down grade higher speed hauls where the truck may be in retard and skid resistance is at a premium.

Where watering alone is insufficient to reduce dust to the required emission levels, we need to look more closely at how dust is formed on a mine road. Dust generation is the process by which fine wearing course material becomes airborne. Such generation is termed a fugitive (or open) dust source. The amount of dust that will be emitted is a function of two basic factors:

- 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. The wearing course clay, silt and fine sand fractions (i.e. 2-75µm) are a good indication of its 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. The consequences of dust generation include:

- loss and degradation of the road wearing course material, the finer particles being lost as dust and the coarser aggregates being swept from the surface or generating a dry skid resistance functional defect;
- decreased safety and increased accident potential for road-users, due to reduced or obscured sight distances, vision and reduced local air quality; and
- higher vehicle operating costs, with dust penetrating the engine and other components resulting in increased rates of wear and more frequent maintenance.

Many products are available which are claimed to reduce both dust and road maintenance requirements for mine roads. Often however, minimal specifications of their properties and no comprehensive comparable and controlled performance trials have been carried out in recognised, published field trials. Additionally, incorrect application techniques and construction methods often result, which lead to considerable scepticism about such products and their overall cost-effectiveness.

**Palliative Selection**

From a mining perspective, the following parameters would define an acceptable dust palliative:

- spray-on application with deep penetration (the ability to penetrate compacted materials), or mix-in applications with minimal site preparation (rip, mix-in and recompact);
straight-forward applications requiring minimal supervision, not sensitive nor requiring excessive maintenance or closely controlled re-applications;

the road should be trafficable within a maximum of 24 hours (short product curing period);

availability in sufficient quantity at reasonable prices;

adequate proven or guaranteed durability, efficiency and resistance to deterioration by leaching, evaporation, ultra-violet light and chemical reaction with wearing course or spillage on road;

effective over both wet and dry seasons; and

evaluated against local and international safety standards and environmentally acceptable.

The broad classes of products available are described on the next page.

The selection matrix below can additionally be used to identify classes of palliative that would suit a certain application. However, the data does not specify the level of performance that could be expected, nor the average degree of palliation or degeneration rate expressed in terms of time from initial establishment and re-application rates. This information would be required as a precursor to an economic assessment of the selected palliative benchmarked against the base case of water-based spraying.

<table>
<thead>
<tr>
<th>Wetting Agents</th>
<th>High PI (&gt;10)</th>
<th>Medium PI (&lt;10)</th>
<th>Stand</th>
<th>Wet weather trafficability</th>
<th>Ramp roads</th>
<th>Heavy traffic</th>
<th>Short term</th>
<th>Long term</th>
<th>Spray-on</th>
<th>Mix-in</th>
<th>Maintainable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
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</tr>
</tbody>
</table>

Notes
I - Initial establishment application
R - Follow-on rejuvenation applications
M - Maintain when moist or lightly watered
SO - Maintain with spray-on re-application
SR - Maintain with spot repairs
<table>
<thead>
<tr>
<th></th>
<th>Hygroscopic Salts</th>
<th>Lignosulphonates</th>
<th>Petroleum-based products</th>
<th>Others (Sulphonated petroleum, Ionic products, Polymers and Enzymes)</th>
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<tbody>
<tr>
<td><strong>Climatic Limitations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Salts lose effectiveness in continual dry periods with low relative humidity. Selection dependant on relative humidity and potential to water road surface.</td>
<td>Retains effectiveness during long dry periods with low humidity.</td>
<td>Generally effective, regardless of climate but will pothole (small diameter) in wet weather where fines content of wearing course is high.</td>
<td>Generally effective, regardless of climate.</td>
</tr>
<tr>
<td><strong>Wearing Course Material Limitations</strong></td>
<td>Recommended for use with moderate surface fines (max 10-20% &lt; 0.075mm). Not suitable for low fines materials or high shrinkage product/PI low CBIR or slippery materials.</td>
<td>Recommended for use where high (&lt;30% &lt; 0.075mm) fines exist in a dense graded gravel with no loose material.</td>
<td>Performs best with low fines content (&lt;10% &lt; 0.075mm). Use low viscosity products on dense fine grained material, more viscous products on looser, open-textured material.</td>
<td>PI' range 8-35 Fines limit 15-55% &lt; 0.075mm. Minimum density ratio 98% MDD (Mod). Performance may be dependant on clay mineralogy (enzymes).</td>
</tr>
<tr>
<td><strong>Treatment Maintenance and Self-repair Capability</strong></td>
<td>Rabilate under moist conditions. CaCl₂ is more amenable to spray-on application. Low shrinkage product materials may shear and corrugate with high speed trucks. Shear can self-repair.</td>
<td>Best applied as an initial mix-in and quality of construction important. Low shrinkage product materials may shear and corrugate with high speed trucks. Tendency to shear or form 'biscuit' layer in dry weather - not self-repairing.</td>
<td>Requires sound base and attention to compaction moisture content. Slow speed, tight radius turning will cause shearing - not self repairing, but amenable to spot repairs.</td>
<td>Mix-in application - sensitive to construction quality. Difficult to maintain - rework. Generally no problem once cured.</td>
</tr>
<tr>
<td><strong>Tendency to Leach out or Accumulate</strong></td>
<td>Leaches down or out of pavement. Repeated applications accumulate.</td>
<td>Leaches in rain if not sufficiently cured. Gradually oxidize and leach out. Repeated applications accumulate.</td>
<td>Does not leach. Repeated application accumulate.</td>
<td>Efficacy depends on the cation exchange capacity of the host material. Repeated applications accumulate.</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>A high fines content may become slippery when wet. Corrosion problems may result.</td>
<td>Generally ineffective if wearing course contains little fines material or there is excessive loose gravel on the road.</td>
<td>Long lasting – more effective in dry climates.</td>
<td>Generally ineffective if material is low in fines content or where loose gravel exists on surface. Curing period required.</td>
</tr>
</tbody>
</table>

**Notes**

1. Plasticity Index
2. California Bearing Ratio (%)
3. Plasticity Index

A poor wearing course material cannot be improved to deliver an adequate performance solely through the addition of a dust palliative. The haul road wearing course material should ideally meet the minimum specifications presented earlier. If not, the inherent functional deficiencies of the material will negate any benefit gained from using dust palliatives. In road surfaces with
too much gravel, dust palliatives do not appear to work effectively, more especially where a spray-on technique is used as opposed to a mix-in. The palliatives do not aid compaction of the surface because of the poor size gradation, nor form a new stable surface. New surface area is created from exposed untreated material while, with a mix-in application, poor compaction leads to damage and ravelling of the wearing course; traffic induces breakdown of the material and eventual dust generation. With regard to water-soluble palliatives, rapid leaching may be problematic. In all cases, it is important to determine if the palliative can be applied with mine water (high TDS and/or salts), or if potable water is a requirement (as would be the case for some bituminous emulsion products where salt would ‘crack’ the emulsion).

In compact sandy soils, polymer, acrylamide and tar bituminous-based emulsion products appear effective where leaching of water-soluble products may be problematic. However, in loose medium and fine sands, bearing capacity will not be adequate for the many products to maintain a new surface and degeneration will occur rapidly. In road surfaces with too much silt, it is unlikely that a dust suppression program will be effective. Excessive silt or clay fractions may lead to a slippery road whilst poor bearing capacity leads to rutting and the need for road rehabilitation or maintenance, which destroys most products. Small-scale potholing has been observed on a number of roads following spray-on application or re-application, as a result of trafficking lifting fine cohesive material from the road. Again, where no depth of treatment has built up, this will lead to the creation of new untreated surface areas.

In general, spray-on applications do not appear appropriate for the establishment of dust treatments, especially with regard to depth of treatment required. A spray-on re-application or rejuvenation may be more appropriate, but only if penetration of the product into the road can be assured, otherwise it will only serve to treat loose material or spillage build-up, which will rapidly breakdown and create new untreated surfaces, and layering can occur, where the build-up of treated fines on the surface leads to a smooth slippery surface devoid of any of the original aggregate in the wearing course.
A spray-on treatment is however useful to suppress dust emissions from the untrafficked roadsides, since it would be easier (and cheaper) to apply and, with the material typically being uncompacted, would provide some depth of penetration and a reduction in dust emissions from truck induced turbulence.

For chemical-based dust suppressants, the average degree of dust palliation and the period over which it is applied can be considerably better than that achievable by water-based spraying alone. 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 palliations. A typical approach is illustrated here.
In all cases, it is important to consider road management philosophy, in particular, to be sure that the use of palliatives or stabilisers will result in reduced road deterioration rates, less maintenance interventions and hence maintain a lower overall rolling resistance. It is obviously counter-productive to use palliatives whose performance exceeds that of the road on which they are applied – since the palliative will be destroyed when maintenance is carried out to fix road-generated deterioration issues.
Introduction to Maintenance

Design and construction costs for the majority of haul roads represent only a small proportion of the total operating and road maintenance costs. The use of an appropriate road maintenance management strategy has the potential to generate significant cost savings - particularly in the light of increases in rolling resistance due to the interactive effects of traffic volume and wearing course deterioration. With large trucks being used, it is inevitable that some deterioration or damage to the road will occur, and this damage needs to be regularly fixed. The better the road is built, the slower the rate of deterioration and thus the less maintenance required. A poor road, however, will quickly deteriorate and will need very frequent maintenance (often to the detriment of other roads in the network).

The management and scheduling of mine haul road maintenance has not been widely reported in the literature, primarily due to the subjective and localized nature of operator experience and required road functionality levels. In most cases, comment is restricted to the various functions comprising maintenance, as opposed to the management of maintenance to minimize overall costs. Some rules of thumb imply adequate serviceability (functionality) can be achieved by the use of one motor grader (and water car) for every 45 000 tkm of daily haulage. The United States Bureau of Mines Minerals Health and Safety Technology Division in their report on mine haul road safety hazards confirm these specifications, but without a clear statement as to what activities comprise road maintenance. Other approaches include blading the road after every 90 truck passes (based on ultra-class RDT). What is clear from this is that road performance varies significantly, as does the material types comprising the wearing course. The latter will have the greatest effect on when a maintenance intervention is scheduled.

What exactly is ‘road maintenance’? There are several key activities that encompass road maintenance, from routine road maintenance (blading or grading), through to resurfacing, rehabilitation and betterment, as defined below;
This Chapter is limited to discussing concepts of routine road maintenance and the associated management systems shown in the table below:

<table>
<thead>
<tr>
<th>System</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ad-hoc blading</td>
<td>Reactionary maintenance management in response to poor haul road functionality. Typically managed by daily inspection of the road network and a subjective assessment of road segment functionality and maintenance priorities.</td>
</tr>
<tr>
<td>Scheduled blading</td>
<td>Road network is maintained according to a fixed schedule or frequency, irrespective of the actual functionality of the road segment being worked.</td>
</tr>
<tr>
<td>Managed maintenance (MMS)</td>
<td>Road network is analyzed to determine rate of functional deterioration of individual segments, based on rolling resistance deterioration, traffic volumes, etc. and segment blading frequency determined to minimize segment and network total road-user costs.</td>
</tr>
</tbody>
</table>

Before road maintenance management is introduced, it is worthwhile to consider why road maintenance is carried out in the first place: its primary purpose is to restore the road to its original operating specification, i.e. to conserve the integrity of the road wearing course by returning or redistributing the gravel surface. In most cases, this will improve a road and reduce its rolling resistance to a more acceptable 2-2.5% minimum. How quickly the road deteriorates again (i.e. rolling resistance increases) will dictate when the next maintenance activity occurs. All too often though, road maintenance is done with little recognition of:
- **where** the maintenance was done (what road segment of the network); and
- **what** was done (blading, dragging, shallow rip and re-grade, etc.)

Keeping records of where and what are important, since this information can tell us whether or not a road is performing well, and if not, what the problem is. The approach is similar to a Root Cause Analysis (RCA) - make sure you identify **why** a segment of road is maintenance intensive before you decide **what** to do about it.

Take, for example, the defect shown in this Figure - a fairly large area of sinkage or potholing on the road. No amount of grading will ‘fix’ this problem since, as was explained earlier, these problems indicate failure deeper in the road layerworks and simply to cut-drag-drop material into the depression will not cure the root cause of the problem. Once the root cause is recognised (structural failure), you can plan to fix the problem correctly (remove softs and backfill with selected compacted base-layer material, re-establish the wearing course and compact).
Root Cause Analysis in Road Maintenance

When grading a road, always apply water before blading, this will assist in creating a good finish to the road and will prevent you from mis-reading any damage to the road. A few examples are shown here to assist in ‘reading’ a road and determining the root-cause of either poor performance or frequent maintenance interventions on the road segment.

Shown here is plenty of loose, unbound material on the road here. It will require frequent blading, due to ravelling. But also consider the geometry here - note how the junction is on grade. Much of the problems here are associated with accelerating laden trucks from stand-still on grade and the high wheel torque which shears the wearing course. Root cause is both the wearing course itself (Sp too low) and the poor junction geometry.

Geometry is most likely the issue here - the crown of the road is non-existent. Water drains to the center of the road. But also consider structure - maybe a soft spot under the road has resulted in this deformation. If that were the case (and DCP probing would confirm this), it would be necessary to remove the softs, backfill with compacted selected waste rock and re-establish wearing course.

When your road looks like this after blading, you have a build-up of fines (clay, mud) on the surface and the grader is simply spreading this around, or if this material persists to depth (100-200mm) then the wearing course is nowhere near specification. Root cause is lack of aggregate in the wearing course - if it’s a spillage issue, deep ripping, remixing and water and recompact the wearing course will bring the material back to specification (if the spillage build-up is deep, blade it off the road first).
If it’s poor wearing course, you’ll need to mix in aggregate (-40mm topsize) to reduce $S_p$ and bring the material back to specification. This would be called ‘rehabilitation’ of the wearing course.

In the following illustration, two issues apparent here, firstly, tyre tracks in the road indicate a wearing course material either poorly compacted or, in its compacted state, failing to reach the minimum 80%CBR required. Extensive rutting is also seen, indicating too soft a structure to support the wearing course. The root cause here would be primarily structural - even the ‘best’ wearing course will not perform well if the underlying support is poor (and thus high surface deflections are experienced).

Finally, in the lower illustration, the edge of the road is in very poor condition. It could quite simply be solved by moving the road boundary markers back onto the edge of the constructed road - if the operating truck width would allow for this. By cutting, drifting and dropping wearing course onto this area will you solve the problem? Unlikely - the root cause here is that the road was built for smaller trucks and now that larger trucks are in use, the road boundary markers have been moved out to accommodate 4x the width of the largest truck. But - the construction width does not extend this far so edge failure will occur. To fix this problem, the mine would have to excavate the full length of the road edge down to in-situ and backfill with a layers of sub-base and base material (or a single layer of selected blasted waste rock) thereby providing protection to the in-situ from the applied wheel loads.

Remember, a RCA for mine road ‘failures’ is just as valid as it would be for any other asset. Excessive maintenance on poorly performing segments of the road network is symptomatic of some underlying design issue. When ‘reading’ the road, work through each design component and question whether or not that component is correct, before moving to the next. In that way, the root cause of the under-performance can be isolated and appropriate solutions planned, scheduled and implemented.
Haul Road Managed Maintenance Systems

Minimising Total Costs Across a Network of Roads

Various road maintenance methods can be applied depending on the type of mining and complexity of the operation. Ideally however, road-user costs need to be minimised and road performance maximised, and a systematic approach to road maintenance management is best. This is referred to as a Maintenance Management System (MMS) and through an analysis of how quickly roads deteriorate under traffic action, how this affects vehicle operating costs and how much it costs to maintain the road (both costs being carried by the mine), an optimum maintenance frequency is found.
Using an ad-hoc or even a routine-based maintenance management system will not deliver minimum total costs. The concept is shown in the figure, where total road-user costs comprise vehicle operating costs (VOC) and road maintenance equipment and application costs. The key to minimising total cost across a network of road segments in a mine is to determine which segments have the greatest influence on cost per ton hauled. It is these segments (invariably ramp or long flat high traffic volume hauls) that should enjoy priority in any maintenance system - since a small reduction in rolling resistance will have the greatest influence on reducing cost per ton hauled across the network. Mine haul road maintenance intervals are closely associated with traffic volumes, operators electing to forgo maintenance on some sections of a road network in favor 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 the maintenance management system (MMS) for mine haul roads. Two elements form the basis of the economic evaluation, namely:

- pavement functional performance - rolling resistance model of deterioration; and
- vehicle operating and road maintenance cost models.

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 wearing course material, traffic volume and speed and geometric (grade and width) characteristics, together with user-specified road maintenance and VOC unit costs, the MMS approach can be used to determine:
the change in road rolling resistance with time and traffic;

- the maintenance quantities as required by the particular maintenance strategy;
- the vehicle operating and road maintenance costs; and
- the optimal maintenance frequency for segments of the network such that total road-user costs are minimised.

This approach is represented in the flow-chart. Cost savings associated with the adoption of a maintenance management system approach are dependant on the particular hauling operation, vehicle types, road geometry and tonnages hauled, etc.

The model can accommodate various combinations of traffic volumes, road segment geometries and wearing course material properties to enable a full road network simulation to be completed.

**Vehicle Operating Cost and Rolling Resistance in MMS**

The first element of an MMS for mine haul roads is based on modeling the variation of vehicle operating costs with rolling resistance. When combined with a road maintenance cost model, the optimal maintenance strategy for a specific network of haul roads, commensurate with lowest overall vehicle and road maintenance costs, may be identified.
The vehicle operating cost model refers to the incremental cost of truck operation with changes in road rolling resistance. The cost model should consider the effect of increasing rolling resistance on fuel consumption, tyres and vehicle wear and repair. However, a reasonable approximation can be determined from fuel consumption alone. The prediction of fuel consumption variation with rolling resistance involves simulation with specific haul trucks to generate a speed model for various road grades. The speed model forms the basis of the fuel consumption model, derived from vehicle simulations coupled with vehicle engine torque (or percentage full throttle) and fuel consumption maps.

Road maintenance cost model

The road maintenance operating cost per kilometer comprises both grader and water car operating costs. Although not contributing directly to a reduction in rolling resistance, the incorporation of the watering costs in the maintenance costs model reflects (the ideal) operating practice in which, immediately before blading, the section of road is watered to reduce dust, erosion and aid blading and recompaction.

Grader and water-car productivities of 0.75 and 6.25 km maintained road per operating hour for each machine, respectively, is typical and correlates with published figures of between 8-18km of maintained road per 16-hour day. However, as the condition of the haul road deteriorates, maintenance becomes more time consuming and the number of blade-passes required to
achieve an acceptable finish when road ‘roughness’ exceeds approximately 3% rolling resistance (RR%) increases. The road maintenance cost model is thus constructed from consideration of the average blade width per pass, road width, RR% before blading, motor-grader productivity curve and hourly cost from which the motor-grader cost per kilometer is found. This cost is then combined with the cost per kilometer of the water-car and other costs to produce a total cost per kilometer for road maintenance.

Example of MMS Application

<table>
<thead>
<tr>
<th>MMS Model: Generic data for all haul road segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck GVM (t)</td>
</tr>
<tr>
<td>Truck UVM (t)</td>
</tr>
<tr>
<td>Drive type</td>
</tr>
<tr>
<td>Replacement cost (Rm)</td>
</tr>
<tr>
<td>Average age (khrs)</td>
</tr>
<tr>
<td>Grader fleet</td>
</tr>
<tr>
<td>Grading hours/day</td>
</tr>
<tr>
<td>Grader Op cost (R/hr)</td>
</tr>
<tr>
<td>Water car fleet</td>
</tr>
<tr>
<td>Watering hours/day</td>
</tr>
<tr>
<td>Water car op cost (R/hr)</td>
</tr>
<tr>
<td>Tyre cost (R)</td>
</tr>
<tr>
<td>Fuel cost (R/l)</td>
</tr>
</tbody>
</table>

Using an example to illustrate the use of MMS, applied to a typical surface mine haul road network. The generic data is shown here.

Data specific to each of 5 segments of a mine haul road network are shown below. A segment is defined where one or more of the model parameters vary, resulting in a slightly different cost structure or road segment performance. Note in the table, a significant number of the values used are out of specification. As will be seen, once the cost of under-performance is established, management action can be prioritised to bring the most critical roads back to specification by rehabilitation.

<table>
<thead>
<tr>
<th>Segments specific data</th>
<th>B02</th>
<th>B03</th>
<th>B04</th>
<th>B05</th>
<th>S RAMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road length (km)</td>
<td>2600</td>
<td>2300</td>
<td>1800</td>
<td>1100</td>
<td>1240</td>
</tr>
<tr>
<td>Width (m)</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>40</td>
</tr>
<tr>
<td>Grade (%, uphill +ve)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>4.5</td>
</tr>
<tr>
<td>Speed (km/h)</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>Daily tonnage (kt)</td>
<td>20.4</td>
<td>20.4</td>
<td>25.5</td>
<td>30.6</td>
<td>100.3</td>
</tr>
<tr>
<td>Material type (1=mix)</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Shrinkage product</td>
<td>189</td>
<td>243</td>
<td>243</td>
<td>243</td>
<td>180</td>
</tr>
<tr>
<td>Grading coefficient</td>
<td>20</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>Dust ratio</td>
<td>0.57</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.64</td>
</tr>
<tr>
<td>Plasticity index</td>
<td>8</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>CBR (%) 100% Mod AASHTO</td>
<td>44</td>
<td>38</td>
<td>38</td>
<td>38</td>
<td>59</td>
</tr>
</tbody>
</table>
By modelling the rate of change in rolling resistance with time (i.e. traffic volumes) for each of the road segments, the lowest total road user cost can be found. Only when the combination of road maintenance and VOC are combined - the ‘total road-user costs’ - can we determine the most efficient approach to road maintenance.

The Figure shows the cost penalty (as percentage change in total road-user costs) associated with under- or over-maintenance of segments. Note how total road-user costs increase when segments B03-B05 are over-maintained - you should only maintain these segments at a three-day interval - more frequent than that and you are incurring excessive road maintenance costs. Note also how road-user costs increase when segment SRamp is not maintained every day - by delaying maintenance on the SRamp to every 2 days, a 5% cost penalty is immediately incurred.

The Figure 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 the B03-B04 segments since the cost penalty associated with sub-optimal maintenance is much lower for these segments.

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. In terms of total cost change per day, significant cost-penalties are associated with over- and under-maintenance of a network of high tonnage mine roads.
What is, however, generic to any analysis of MMS for a network of roads is that to reduce costs across the board, road performance needs to be maximised. This is best achieved through an integrated design approach, where geometric, structural and functional design components contribute to a road that has only a slow rate of deterioration, hence rolling resistance (and thus VOC) do not increase substantially and maintenance intervals can be extended without significant cost penalties.
Benchmarking Rolling Resistance and Functional Performance

Rolling Resistance Assessment

In order to make informed road maintenance decisions, some basis of comparison should be established with which to compare segments of road across the network. This comparison is based on the functional defects described previously and - as stated earlier - it is possible to equate functional defects with rolling resistance - hence the condition of a road has a direct effect on rolling resistance.

Two approaches are presented here, the first based on a predictive model of road deterioration which uses truck, traffic and wearing course material parameters to evaluate rolling resistance changes with time, and the second method a qualitative visual assessment, based on the same methodology but simplified in terms of the ‘defect’ scores used to evaluate current road conditions.

Modeling rolling resistance changes over time

The rolling resistance of a haul road is primarily related to the wearing course material used, its engineering properties, and the traffic speed and volume on the road. These dictate, to a large degree, the rate of increase in rolling resistance. Ideally, road rolling resistance should not increase rapidly - which implies that those road defects (roughness defects) leading to rolling resistance should also be minimized. This can be achieved through careful selection of the wearing course or sheeting material, which will minimize, but not totally eliminate, rolling resistance increases over time (or traffic volume).

To estimate rolling resistance (RR) at a point in time, an estimate of the roughness defect score (RDS) is required, and this can be determined from an initial estimate of the minimum and maximum roughness defect scores (RDSMIN, RDSMAX), together with the rate of increase (RDSI). Rolling resistance at a point in time (D days after road maintenance) is then estimated from a minimum value (RRMIN) and the associated rate of increase.

The equations given below can be used, together with the parameters and variables defined in the Table that follows. When using these equations, care should be taken to ensure the parameters limits are comparable to the values used in the original research.
\[
\text{RDS} = \text{RDSMIN} + \left[ \frac{\text{RDSMAX} - \text{RDSMIN}}{1 + \exp^{\text{RDSI}}} \right]
\]

Where; 
\[
\text{RDSMIN} = 31.1919 - 0.05354\text{SP} - 0.0152\text{CBR}
\]
\[
\text{RDSMAX} = 7.6415 + 0.4214\text{KT} + 0.3133\text{GC} + 0.4952\text{RDSMIN}
\]
\[
\text{RDSI} = 1.768 + 0.001.D(2.69\text{KT} - 72.75\text{PI} - 2.59\text{CBR} - 9.35\text{GC} + 1.67\text{SP})
\]

and
\[
\text{RR} = \text{RRMIN} + \text{RDS}.\exp^{(\text{RRI})}
\]

Where;
\[
\text{RRMIN} = \exp^{(-1.8166 + 0.0028V)}
\]
\[
\text{RRI} = -6.068 - 0.00385\text{RDS} + 0.0061V
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RDS</td>
<td>Roughness defect score</td>
</tr>
<tr>
<td>RDSMIN</td>
<td>Minimum roughness defect score immediately following last maintenance cycle</td>
</tr>
<tr>
<td>RDSMAX</td>
<td>Maximum roughness defect score</td>
</tr>
<tr>
<td>RDSI</td>
<td>Rate of roughness defect score increase</td>
</tr>
<tr>
<td>RR</td>
<td>Rolling resistance (N/kg)</td>
</tr>
<tr>
<td>RRMIN</td>
<td>Minimum rolling resistance at (RDS) = 0</td>
</tr>
<tr>
<td>RRI</td>
<td>Rate of increase in rolling resistance from RRMIN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Vehicle speed (km/h)</td>
</tr>
<tr>
<td>D</td>
<td>Days since last road maintenance</td>
</tr>
<tr>
<td>KT</td>
<td>Average daily tonnage hauled (kt)</td>
</tr>
<tr>
<td>PI</td>
<td>Plasticity index</td>
</tr>
<tr>
<td>CBR</td>
<td>100% Mod. California Bearing Ratio of wearing course material</td>
</tr>
</tbody>
</table>
The Figure shows a typical estimate of rolling resistance (given here as N/kg, so multiply by 9.81 to give rolling resistance as a percentage) estimated using the equations above and data in the figure. It also compares the model estimates to the actual rolling resistance values determined at that location.

**Qualitative rolling resistance assessments**

Rolling resistance can also be estimated from a qualitative visual evaluation. A road defect classification system can be applied in which the key defects influencing rolling resistance are identified and the product of defect degree (measured on a scale of 1-5) and extent (measured on a scale of 1-5) are scored for each of these defects using the tables that follow. The sum of the individual defect scores thus rated (equivalent to the RDS discussed earlier) can be converted using the scoring sheet and figure to give a rolling resistance for the segment of haul road under consideration.

The evaluation method is based on a visual assessment of a defect ‘degree’ (i.e. how bad) and an ‘extent’ (i.e. how much) of the road is affected. The defects considered to have the greatest influence on mine haul road rolling resistance are:

- potholes;
- corrugations;
- rutting;
- loose material; and
- stoniness - fixed (in wearing course).
To ‘score’ these defects in terms of degree or extent, the following descriptions can be used, or the following visual equivalents (only defect degree 1, 3 and 5 given in the Figure).

Where the defect is not evident on the road, a defect degree of 1 and extent of 1 is scored.

<table>
<thead>
<tr>
<th>Description of defect extent or degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extent Score</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Extent</td>
</tr>
<tr>
<td>Defect degree score</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Potholes</td>
</tr>
<tr>
<td>Corrugation</td>
</tr>
<tr>
<td>Rutting</td>
</tr>
<tr>
<td>Loose material</td>
</tr>
<tr>
<td>Stoniness - fixed in wearing course</td>
</tr>
</tbody>
</table>
The scoring sheet in the next Figure is used, in conjunction with the graphic, to convert RDS to Rolling Resistance (%) using the line representing the vehicle speed on the road (10 to 50km/h in increments of 10km/h).
# Mine Haul Road Rolling Resistance Visual Evaluation

<table>
<thead>
<tr>
<th>DATE</th>
<th>EVALUATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROAD</td>
<td>VEHICLE SPEED km/hr (V)</td>
</tr>
<tr>
<td>CHAINAGE</td>
<td>TRAFFIC kt/day</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DEFECT</th>
<th>RDS (Rolling resistance)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DEGREE (1-5)</td>
</tr>
<tr>
<td>Potholes</td>
<td>x</td>
</tr>
<tr>
<td>Corrugations</td>
<td>x</td>
</tr>
<tr>
<td>Rutting</td>
<td>x</td>
</tr>
<tr>
<td>Loose material</td>
<td>x</td>
</tr>
<tr>
<td>Stoniness - fixed</td>
<td>x</td>
</tr>
</tbody>
</table>

**Total Roughness Score (RDS):**

**Estimated Rolling Resistance (%):**

Refer to graph for rolling resistance percentages.

---

![Graph for rolling resistance percentages](image)
In this Figure, the potholes seen in the road would typically score a ‘degree’ of 5 and an ‘extent’ of 2, giving an individual defect score for pothole defect of (2×5) = 10.

In this Figure, the potholes seen in the road would typically score a ‘degree’ of 2 and an ‘extent’ of 5, giving an individual defect score for pothole defect of (5×2) = 10.
Functional Performance Assessments

The approach outlined previously can be extended to cover all the defects experienced on a road, to assess the functionality of a road at a point in time. The recording sheet shown below can be used to assess a ‘functional defect score’ (DS) from a minimum value of 12 to a maximum of 300.

<table>
<thead>
<tr>
<th>DATE</th>
<th>EVALUATOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROAD</td>
<td>VEHICLE SPEED km/hr (V)</td>
</tr>
<tr>
<td>CHAINAGE</td>
<td>TRAFFIC kt/day</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DEFECT</th>
<th>DS (Functionality)</th>
<th>DEFECT SCORE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DEGREE (1-5)</td>
<td>EXTENT (1-5)</td>
</tr>
<tr>
<td>Potholes</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Corrugations</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Rutting</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Loose material</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Stoniness - fixed</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Dustiness</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Stoniness - loose</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Cracks - longitudinal</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Cracks - slip</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Cracks - crocodile</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Skid resistance - wet</td>
<td>x</td>
<td>=</td>
</tr>
<tr>
<td>Skid resistance - dry</td>
<td>x</td>
<td>=</td>
</tr>
</tbody>
</table>

**TOTAL FUNCTIONAL DEFECT SCORE (DS)**

\[ \sum (\text{Defect degree} \times \text{defect extent}) \]

- **Road maintenance recommended if:**
  - Any critical defect score exceeded
  - DS > 140
- **Road maintenance imminent, but road trafficable**
  - 65 < DS < 140
- **Road is in good condition, no road maintenance required**
  - DS < 64

**Drainage**
- On road
- Roadside

**Erosion**
- Longitudinal
- Cross
Individual mine sites will need to set their own ‘maintenance intervention thresholds (identified in table as asterisk *) at which some road maintenance activity is triggered when exceeded. In the table, typical values are as follows:

Road maintenance is recommended if:

- any single critical functional defect exceeds limits; or
  - total functional defect score (DS)$\geq140$.

- Road maintenance imminent but still trafficable when $65\leq DS < 139$.

- Road in good condition, no immediate maintenance needs when $DS < 64$.

The decision whether or not to maintain the road is not only based on the total DS, but also on critical (identified in table as hash #) individual defect scores too, since these generally adversely affect safety and trafficability. These critical individual defects are generally corrugations, loose material, fixed stoniness, dustiness and wet and dry skid resistance and each has a critical functional defect limit which should also be considered in addition to the overall DS. These values used here are specific to each mine site and it’s operating conditions. Since functionality and road performance in general is influenced by drainage and erosion, it is useful to comment on these two aspects also - poor drainage and/or excessive erosion on the road would normally trigger some maintenance activity in its own right.

The first 5 defects are scored as described in the previous section for rolling resistance, using the visual assessments provided. The scoring for the extra defects considered from a functionality perspective is given in the Figure on the next page.

Another approach is to assess road functionality according to the chart given here. Functional performance acceptability criteria (limits for desirable, undesirable and unacceptable) should be based on your mine’s operating experience - average values for many mines are shown here - but mostly operating in dry and temperate environments. Used on a daily basis, this chart is useful to record how a road deteriorates over time - a road that always returns values in the red sector is probably a good candidate for rehabilitation. If your road segment is always scoring in the yellow and red sectors - even despite frequent maintenance interventions - then it is worth re-evaluating the wearing course functional design and possibly even the structural and/or geometric designs - since the poor performance is not in itself indicative of poor maintenance - rather an underlying design deficiency.
<table>
<thead>
<tr>
<th>DEFECT</th>
<th>VISUAL DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Degree 1</td>
</tr>
<tr>
<td>Dustiness</td>
<td><img src="image1" alt="Image" /></td>
</tr>
<tr>
<td>Stones – loose on road</td>
<td><img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>Cracks – longitudinal</td>
<td><img src="image7" alt="Image" /></td>
</tr>
<tr>
<td>Cracks – slip</td>
<td><img src="image10" alt="Image" /></td>
</tr>
<tr>
<td>Cracks – crocodile</td>
<td><img src="image13" alt="Image" /></td>
</tr>
<tr>
<td>Skid resistance – wet</td>
<td><img src="image16" alt="Image" /></td>
</tr>
<tr>
<td>Skid resistance – dry</td>
<td><img src="image19" alt="Image" /></td>
</tr>
</tbody>
</table>
Mining Roads

It can also be useful to use this concept in day-to-day road maintenance planning. If roads are evaluated at start of shift, they can be marked with red, yellow or green cones to indicate what segments should enjoy maintenance priority (red). This approach is also useful for truck drivers - it helps them anticipate road (and traffic) conditions and thus operate their trucks accordingly. In either case it is important to retain these records and evaluate how each segment of road changes over time and traffic, to identify those segments of the network that continually under-perform, the reasons for this (using the typical defect to identify the root-cause) and thus the most appropriate remediation strategy.
Bibliography

To aid readability and clarity of the concepts presented in these notes, in-text citations have not been used. However, you may wish to refer to the following texts, which form the basis of the design and construction guidelines summarised here.


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.


Davey, T. and McLeod, M. 2002. Assessing Haul Road Condition using Application Severity Analysis (ASA) – Version 8, 16 October, Cat Global Mining Asia Pacific


Lay, M.G. 1998. Handbook of Road Technology Volume 1 Planning and Pavements. 3rd Ed. Gordon and Beach Science Publishers,. (see section 11.2.3)


Thompson, R.J. 2011. CBR and mechanistic structural design methodologies for mine haul roads. Submitted to Trans(A) (Mining Technology) Institute of Mining, Metallurgy and Materials (IMMM). Forthcoming.


ADDITIONAL ELECTRONIC REFERENCES

Haul Road Design - copies of technical papers, etc.
http://mining.curtin.edu.au/people/staff_profiles/roger_thompson_profile.cfm


Kaufmann and Ault (1977) Haul Road Guidelines
www.cdc.gov/niosh/mining/pubs/pdfs/ic8758.pdf

Haul Road Inspection Handbook (1999)

Blind Areas Report (Haul Trucks)
http://www.usmra.com/repository/category/mobile_equipment/
BASFinalReport.pdf

EMESRTgate – EarthMoving Equipment Safety Roundtable - Surface

INFOMINE Technology Review – Mine Haul Roads

Caterpillar Global Mining Haul Road Design and Management

Training Resource: IACET/UBC and ISO TC232 accredited