PRINCIPLES OF MINE HAUL ROAD DESIGN AND CONSTRUCTION

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Principles of Mine Haul Road Design and Construction

Introduction to Course

This guide introduces readers to the key concepts & principles of mine haul road design, from philosophy of provision, road rolling resistance and the cost penalty of poor road performance, road building material selection and characterisation, road-user (truck and traffic) requirements, road design, through to performance benchmarking and evaluation.

Since this is a generic guide, content focuses on design concepts and principles rather than on any particular local 'conventional' procedures and 'established' practice except for the application-specific case-studies and supporting data which are drawn primarily from design cases for mines in arid and semi-arid regions. Participants should consider the potential influence of local administrative and regulatory policy, climatic variations or operational warrants and in most cases it will be necessary to determine and understand these local matters in the context of the broader generic concepts given here. This guide aims to provide a sound basis for that understanding and to guide readers to the next phases of a haul road design or rehabilitation/improvement project.

Particular attention is given to assisting readers in understanding the principles of provision and design, together with defining terminology and resources, in order to apply these concepts to local requirements, procedures and operational warrants. The guide provides 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?
  - geometric design requirements
  - structural design requirements and methods
  - functional (wearing course/sheeting design requirements and method
  - maintenance management and design
- 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.
Acknowledgements

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Prof Alex T Visser (Civil Engineering, University of Pretoria) is acknowledged for his contributions as colleague with whom many of the haul road design and management concepts were originally developed. Contributions to aspects of the mine haul road design techniques described here, by Profs GA Fourie, PS Heyns and RAF Smith from Pretoria University, South Africa. Further contributions are acknowledged from Damir Vagaja, formerly of the ARRB and Principal Consultant at RTSM Consulting, Dave Tulloch, Principal Consultant at RSTS and the Haul Roads Optimisation Alliance (Australia).

Given the objectives of the guide, to aid readability and clarity of the concepts, in-text citations have not been used, although the notes draw heavily on many of the contributors to this field. The aim is to present available information in collated and readable form, rather than to present new or unproven knowledge and concepts. Any inadequacies or imprecision in the referencing of these sources is a result of this approach, and I do wish to acknowledge all those whose knowledge I have drawn on. To this end, you may wish to refer to the full list of texts which resourced this work and which form the basis of the design and construction guidelines summarised here. These are presented in the Bibliography section.

Disclaimer

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Principles of Mine Haul Road Design and Construction

Contents

Introduction to Course ................................................................. i
Acknowledgements ....................................................................... ii
Disclaimer .................................................................................... ii

INTRODUCTION TO HAUL ROAD DESIGN AND CONSTRUCTION ........................................ 1-1

Learning Objectives ...................................................................... 1-1
Basic Design Requirements For Haul Roads ................................ 1-2
Design Methodologies ................................................................... 1-6
‘Design’ or Just ‘Build’ A Road? ..................................................... 1-6
An Integrated Design Approach .................................................... 1-8
Fundamental Safety Considerations .............................................. 1-11
Rolling Resistance - Manage and Minimise ................................ 1-14
Haul Road Classification ................................................................. 1-20

Truck Related Design Requirements ........................................... 1-20
Approaches to Haul Road Classification ....................................... 1-21
Selecting and Using Appropriate Truck Data in Design Guidelines .......................................................................................... 1-26

HAUL ROAD DESIGN AND CONSTRUCTION – TERMINOLOGY AND RESOURCES .............. 2-1

Learning Objectives ...................................................................... 2-1
What Are We Designing and Building? ........................................ 2-2
Sub-grade / In-situ ........................................................................ 2-3
Fill ............................................................................................... 2-3
Sub-base ....................................................................................... 2-3
Base .............................................................................................. 2-4
Wearing Course/Sheeting .............................................................. 2-4
Components of an Integrated Road Design ................................... 2-5
Why An Integrated Design Approach? ......................................... 2-5
Geometric Design .............................................................................................................. 2-7
Structural Design ............................................................................................................... 2-8
Functional Design ............................................................................................................. 2-8
Maintenance Design ......................................................................................................... 2-9
Road Construction Resources ......................................................................................... 2-10
What Do You Need To Make A Road? .............................................................................. 2-10
Equipment for Road Building ......................................................................................... 2-11
Materials for Road Building ........................................................................................... 2-15

FUNDAMENTAL GEOMETRIC DESIGN CONSIDERATIONS ........................................ 3-1
Learning Objectives ........................................................................................................ 3-1
Geometric Design - Introduction ...................................................................................... 3-2
Stopping & Sight Distance Considerations ...................................................................... 3-3
Sight Distances .................................................................................................................. 3-7
Truck Operator Blind Spots ............................................................................................. 3-8
Vertical Alignment Issues ................................................................................................. 3-10
Optimal and Maximum Sustained Grades ....................................................................... 3-11
Horizontal (Longitudinal) Alignment Issues .............................................................. 3-13
Width of Road .................................................................................................................. 3-13
Turning Circle of Large Haul Trucks ............................................................................. 3-14
Curvature and Switchbacks ............................................................................................ 3-15
Curve Super-elevation (Banking) .................................................................................... 3-17
Run-out (Development of Super-elevation) .................................................................... 3-19
Cross-fall, Crown or Camber .......................................................................................... 3-19
Intersection Design .......................................................................................................... 3-21
Combined Alignment ....................................................................................................... 3-23
Safety Berms ..................................................................................................................... 3-23
Ditches and Drainage ........................................................................................................ 3-24

HAUL ROAD STRUCTURAL DESIGN AND SPECIFICATION .................................... 4-1
Learning Objectives ......................................................................................................... 4-1
Introduction to Structural Design of Haul Roads ........................................................... 4-2
Generic Construction Specifications ............................................................................... 4-2
Structural Design Methodologies ................................................................................... 4-4
BIBLIOGRAPHY.................................................................................................................. 7-1

General Concepts in Mine Haulage and Road Design......................................................... 7-1
Safety in Mine Haulage ....................................................................................................... 7-2
Geometric Design of Mine Roads....................................................................................... 7-3
Structural Design of Mine Haul Roads .............................................................................. 7-3
Functional Design of Mine Haul Roads ............................................................................ 7-5
Mine Haul Road Maintenance and Management............................................................... 7-6
Additional Electronic References ....................................................................................... 7-7
# 1 INTRODUCTION TO HAUL ROAD DESIGN AND CONSTRUCTION

## Learning Objectives

<table>
<thead>
<tr>
<th>Learning Objectives</th>
<th>Knowledge and understanding of;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basic design requirements for mine haul roads; geometric, structural, functional, maintenance designs.</td>
</tr>
<tr>
<td></td>
<td>Generic cost model for haulage operating costs as part of the overall mining costs structure, as well as the operating costs model for an individual truck.</td>
</tr>
<tr>
<td></td>
<td>The design methodologies; empirical design approaches versus integrated design, benefits of the integrated design methodology.</td>
</tr>
<tr>
<td></td>
<td>Fundamental safety considerations of mine roads, design and audit approaches, how to combine the requirements of both to build and operate safe roads.</td>
</tr>
<tr>
<td></td>
<td>Rolling resistance, how it is generated, managed and minimized; the effect of tyre penetration and the role of road defects.</td>
</tr>
<tr>
<td></td>
<td>Haul road classification; understanding the basis for haul road classification and its role in road design and management.</td>
</tr>
<tr>
<td></td>
<td>Truck related design requirements; what basic information is needed in support of road design?</td>
</tr>
<tr>
<td></td>
<td><strong>Application of;</strong></td>
</tr>
<tr>
<td></td>
<td>Speed-rimpull-gradeability data in determining impact of rolling resistance on haulage operations.</td>
</tr>
<tr>
<td></td>
<td>Truck data; sourcing and use in developing design classification systems and design guidelines</td>
</tr>
<tr>
<td></td>
<td><strong>Calculate and predict;</strong></td>
</tr>
<tr>
<td></td>
<td>Estimates of rolling resistance as a function of tyre penetration.</td>
</tr>
<tr>
<td></td>
<td>Effective grade as a function of rolling resistance and road grade.</td>
</tr>
<tr>
<td></td>
<td>Haul truck speed based on effective grade.</td>
</tr>
<tr>
<td></td>
<td>Change in haul cycle times due to changes in rolling resistance.</td>
</tr>
</tbody>
</table>
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. If not, a critical production asset becomes a significant operating liability.

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.

Some highway engineering concepts 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, mean that mine road design and management procedures are quite different.

Most mine operators will agree that a strong relationship exists between well-constructed and - maintained roads and safe, efficient mining operations. Large modern surface mining operations should generally incorporate high standards of road design work into the overall mine plan. The result is usually a well-constructed road that is safe to operate and easy to maintain. This situation can be quite different for smaller surface mining operations where either only a few vehicles are used in the transport of material or traffic volumes are comparatively low. Larger operations usually exhibit a stronger and more well-defined management philosophy in which special localized
consideration is often given to haul road design, management and maintenance, whereas smaller operations, by virtue of their size, generally operate without such extensive design and management input.

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.

Where design and management input is lacking (i.e. often when using an empirical approach based on local experience) – safe, economically optimal roads eventually result – but the learning curve is shallow and slow. This approach does not lend itself to an understanding of the road design process and more importantly, if haul road safety is sub-standard, it does not easily allow the underlying cause of the unsafe condition or the role of road design in contributing to an accident (as a root-cause or associated factor) to be identified.

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

The content of the USBM design guidelines was developed primarily in response to haulage accidents, but also included current practice information from mining companies and equipment manufacturers. Content covered such aspects as road alignment (both vertical and horizontal), road cross-section, construction materials, surfacing materials, road width, cross-slope and berm design, together with traffic control and drainage provisions, as was suggested criteria for road and vehicle maintenance and for runaway vehicle safety provisions.

A more rigorous approach to categorize the various issues that must be addressed in a haul road design needs to consider;
- The geometric design

Commonly the starting point for any haul road design and refers to the layout and alignment of the road, in both the horizontal and vertical plane, stopping distances, sight distances, junction layout, berm walls, provision of shoulders and road width variation, within the limits imposed by the mining method. The ultimate aim is to produce an efficient and safe geometric design, which can only be achieved when sound geometric design principles are applied in conjunction with the optimal structural, functional and maintenance designs.

- The structural design

Provides haul road ‘strength’ to carry the imposed loads over the design life of the road without the need for excessive maintenance, caused by deformation of one or more layers in the road – most often soft, weak or wet in-situ materials below the road surface.

- The functional design

Centred on the selection of wearing course (or surfacing) materials where the most suitable choice and application is required which minimizes the rate of defect formation or rolling resistance increase, in the road surface, which would otherwise compromise road safety and performance. 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 carcase, 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.
The maintenance design which identifies the optimal frequency of maintenance (routine grading) for each section of haul road in a network, thus maintenance can be planned, scheduled and prioritized for optimal road performance and minimum total (vehicle operating and road maintenance) costs across the network. This is especially important where road maintenance assets are scarce and need to be used to best effect. 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 it. The better the roads are built, the slower the deterioration rate and the less maintenance will be required.

The use of an appropriate road maintenance management strategy will generate significant cost savings by virtue of a better understanding of the relationship between wearing course material degeneration rates (manifest as increasing rolling resistance on the road) and its influence on both cost per tonne hauled and the cost of road maintenance itself.

A little time and effort spent in building to 'specification' will result in long term operational 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.

How is this achieved practically? Below are various approaches to mine road design from which the ideal or 'integrated' design approach is determined.
Design Methodologies

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, an empirical design does not easily allow the underlying or root-cause of the poor performance to be identified.

‘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 planning and 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 below shows a (simplified) 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, 470 tons per truck-hour can be produced – an increase of 38% or 500,000 tons per annum. If an annual excavation target of 10Mt 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.

This rule of thumb will be explored in more detail in the following sections. What is clear however is that 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.
An Integrated Design Approach

The operating performance of a mine road can be subdivided into four distinct design components as shown earlier, and when designing and constructing a haul road for optimal performance, these design components are best addressed using an integrated approach. If one design component is deficient, the other components may 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 operating, downtime and repair costs. The cure, however, is not necessarily just ‘more frequent maintenance’; no amount of maintenance will fix a poorly-designed road.

### HAUL ROAD NETWORK DESIGN

**BENCHMARKING**

<table>
<thead>
<tr>
<th>Location of assessment</th>
<th>Date</th>
<th>Time</th>
<th>Truck speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D4 top end</td>
<td>10/25/06</td>
<td>12:38:07pm</td>
<td>20</td>
</tr>
</tbody>
</table>

**FUNCTIONALITY ASSESSMENT**

- Potholes (d): 1
- Potholes (e): 1
- Corrugations (d): 2
- Corrugations (e): 2
- Rutting (d): 2
- Rutting (e): 2
- Loose material (d): 2
- Loose material (e): 2
- Stones fixed (d): 2
- Stones fixed (e): 2
- Dustiness (d): 3
- Dustiness (e): 3
- Stones loose (d): 2
- Stones loose (e): 2
- Crack longit (d): 1
- Crack longit (e): 1
- Crack slip (d): 1
- Crack slip (e): 1
- Crack croc (d): 2
- Crack croc (e): 2
- Skid resistance W (d): 3
- Skid resistance W (e): 3
- Skid resistance D (d): 3
- Skid resistance D (e): 3
- Comment functional: grade breaks on ember on
- Comment geometric: grade breaks

**FUNCTIONAL DEFECT SCORING**

- Score: 64
- Compliance (%): 79
- Rolling resistance (%): 3.1

**Comments**

Wearing course is adequate, but with isolated large stones in wearing course.

Main problem is grade breaks towards top of road and some cross-erosion due to poor side drainage.

Some rutting on laden side of road. Compaction required as road is extended up over dumps.

Rolling resistance is acceptable but could be reduced by grading out the ruts and re-compacting the laden side.
Design and management of haul road systems should also be approached holistically, especially with regard to the benefits achieved from various solutions to enhance productivity. Whilst, for instance, trolley-assist may improve cycle times and reduce cost per tonne hauled, it is first necessary to evaluate the extent to which an existing haul road network meets optimal design requirements, typically as illustrated above, before resorting to solutions that do not directly address the key deficiencies of the existing road system. The recommended approach is therefore to assess the extent to which the asset (the current road network) exhibits scope for improvement and, once optimized, then revert to resource supplementation to leverage these benefits through optimal asset and resource interaction.

This illustration shows the broad approach to mine haul road design using an integrated approach. It differentiates between the design and operational phases of a road and highlights where modifications can be made to the process to optimise performance.

A more detailed depiction is shown below, based on the geometric, structural (layerworks), functional (wearing course) and maintenance management components, together with an evaluation methodology for the selection and application of dust palliatives. These design components and the detailed design considerations form the basis of the following sections of the training course.
**Basic Design Data**
- Truck type, wheel and axle loads
- Traffic volumes
- Design life of road
- Category of road required
- Construction materials available
- Unit costs

**Geometric Design**
- Truck types and dimensions
- Alignment in both the horizontal and vertical planes
- Road width
- Stopping distances
- Sight distances
- Junction layout
- Berm walls and shoulders
- Drainage design on- and off-road

**Structural Design**
- Performance index and limiting strain criteria
- CBR or Mechanistic design
- Life of road and traffic volumes
- Layerworks material strengths
- In-situ material

**Functional Design**
- Wearing course selection and blending
- Critical service defects
- Rolling resistance progression
- Palliation or stabilisation required?

**Stabilisation or Palliative Cost or Performance Mismatch**
- Modify wearing course material

**Palliative Application Options**
- Match palliative product to wearing course specifications
- Evaluate application rates
- Performance of palliatives
- Re-application rates
- Cost effective?

**Stabilisation Application Options**
- Match stabilisation product to layer specifications
- Evaluate application rates
- Safety and health implications
- Cost effective?

**Performance Optimum for Minimum Total Road-User Costs**

**Maintenance Management Design**
- Establish maintenance intervals for network of roads
- Determine costs and quantities associated with maintenance and road-user cost models
- Road maintenance schedule for minimum total road-user costs
- Schedule appropriate for road maintenance assets?
Fundamental Safety Considerations

To further reduce and eliminate accidents and fatalities, prevention strategies evolve from sound fundamental engineering design aspects, enforcement and education, to encompass human error behavioural analysis, to better understand and control or eliminate hazards.

In a mining environment, the mine road network generally includes;

- in- and ex-pit (light- and heavy-vehicle) haul roads
- ex-pit access roads
- infrastructure service roads.

Although each of these roads requires a different approach to design, there is commonality in terms of a broad safe systems approach, such as one outlined by the Australian Transport Council, in which the identification, removal or amelioration of road elements which may contribute to hazards and incidents is a key component. A safe system acknowledges that humans are fallible, error is inevitable, and that when it does occur the (mine haul) road system makes allowance for these errors so as to minimise the level of hazard associated with the risk.

The safe systems approach when applied to mine roads requires, in part (modified after Australian Transport Council and RTSM):

- designing, constructing and maintaining a road system (roads, vehicles and operating requirements) so that forces on the human body generated in incidents are generally less than those resulting in fatal or debilitating injury;
- improving roads and adjoining areas to reduce the risk of incidents and minimise hazards: Designing ‘forgiving’ haul roads and roadsides which allow a margin of recovery from error;
- managing speed, taking into account the speed-related risks on different parts of the road system.
Using this approach, and recognising the three distinct mine road systems; in- and ex-pit haul roads, ex-pit access roads and infrastructure service roads, the key elements of the safe systems approach are shown here, modified after the Australian Transport Council approach and RSTM.

In the mining environment, safer vehicles are addressed through local and international earthmoving equipment standards, together with forums such as the Earth Moving Equipment Safety Round Table (MIRMGATE) which identifies equipment risks, hazards and priority safety topics for surface earth moving equipment and develops associated design philosophies. Safer roads are addressed both through design and safety auditing. Access and infrastructure service road design is primarily addressed through existing design guidelines for unsealed ‘conventional’ roads.

The integrated road design methodology shown earlier considers each component as part of the overall ‘design’ process, but does not integrate that within a broader approach whereby other road types and road-safety elements are considered in the context of the wider network of roads.

Safety audit systems (such as the AustRoads method and the RSTM system) have been used on public road networks for a number of years and recently they have also been applied in mining operations where typically the following specific mine-site road-safety auditing elements are included:

- evaluation of current safety system documentation, standards and processes.
- vehicle and/or road-user interactions;
- speed management;
- geometric layout including potential area of traffic conflict;
- signage, delineation and lighting;
- parking arrangements;

The combination of design and audit form the basis for developing a safer in- and ex-pit heavy vehicle mine haul road, and the following figure illustrates the combined approach. This course, however, focuses purely on the design aspects, which are the fundamental elements or building blocks of safety audit systems.
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 10kg/t = 1% rolling resistance or 1% equivalent grade.

Rolling resistance is defined as the force required to maintain a vehicle at a steady speed on level ground and is a function not only of the gross vehicle mass and drive-train characteristics, but also of the type and condition of the tyres and the road surface on which the vehicle is operated (together with other smaller additional resistances, such as wind resistance, etc.).

Rolling resistance 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 centimetre 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 the illustration alongside, mud is visible up to tread depth (about 55mm which implies tyre sinkage into the road surface (west, muddy) and a rolling resistance of approx. 4.8% (from empirical relationship above) under these conditions.
The following table summarises typical values.

<table>
<thead>
<tr>
<th>Rolling resistance (%)</th>
<th>Road surface conditions (built from unbound gravel materials)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Strong layerworks and hard, compacted (stabilised) well-built and maintained road, no tyre penetration/deflection discernable</td>
</tr>
<tr>
<td>2-3</td>
<td>Intermediate strength layerworks, compacted (stabilised), well-built and frequently maintained road, with minimal (&lt;25mm) tyre penetration/deflection</td>
</tr>
<tr>
<td>3-5</td>
<td>Weak layerworks or surfacing material, 25-50mm tyre penetration/deflection, rutted and poorly maintained</td>
</tr>
<tr>
<td>5-8</td>
<td>Weak layerworks or surfacing material, 50-100mm tyre penetration/deflection, rutted and poorly maintained</td>
</tr>
</tbody>
</table>

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.

An alternative approach to rolling resistance evaluation will be introduced later, in the Chapter on Maintenance Management, where ‘defects’, or characteristics failures of the road will be used to qualitatively determine a rolling resistance. This approach enables more realistic determinations of rolling resistance to be made, based on the actual road surface conditions and each defects’ contribution to rolling resistance.

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 %**
A typical performance chart for propulsion (rimpull-speed-gradeability) and braking (retard) are shown below.

These type of charts can be used to evaluate the impact of rolling resistance on truck performance, to derive a more accurate estimation of the rule of thumb previously mentioned where, for an ultra-class truck (with approx. 4.2kW/t of GVM);

- 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.

To use these charts in developing an estimate of the impact of rolling resistance on truck performance, the following basic steps can be followed;

- Determine which curve on the chart to use – where effective grade is against the load (uphill), propulsion curves are read, whereas if effective grade is with the load (downhill), then the brake curve is used.
- As an example, for a segment of a haul cycle – RAMP1 is built at a grade of 8% and has road rolling resistance of 2%. If the truck is working laden against the grade, the truck speed can be determined by;
  - Calculating effective grade (8%+2%) = 10%;
  - Selecting the 10% effective grade line, follow this line diagonally to it’s intersection with (in this case) the vertical line representing the full truck;
- Using a straight edge, project this point horizontally to the left until it intersects with the propulsion curve;
- Using a straight edge, project this intersection point vertically down to read the speed of the truck.

Using the 10% effective grade against the load and the propulsion curve in the chart as shown below, a truck speed of 14km/h is found. Using the same logic, but in this case for the empty truck return journey at an effective grade of (8%-2%) = 6%, the maximum truck speed is 64km/h from the intersection of the 6% effective grade line with the empty truck vertical line, projected (right) to the retard speed curve - (but whether it is safe to travel down a 6% ramp at this speed will be examined later in the course).

The table below summarises these results, and also shows the same calculations repeated for a 1% increase in rolling resistance, which in this case results in a 14% decrease in truck speed when distance is taken into account. This method can then be repeated for the remaining segments of the haul cycle to determine the overall increase in cycle time associated with a 1% increase in road rolling resistance.
Developing this approach further enables the effect of rolling resistance increase to be seen for any grade of road (assuming truck operated laden against the grade), as shown below. On a ramp road of 8-10% grade (against the load) and a basic rolling resistance of 2%, an additional 1% rolling resistance will reduce truck speed by 10-13%, whilst on a flatter surface road of 0-2% grade (against the load) and a basic rolling resistance of 2%, an additional 1% rolling resistance will reduce truck speed by between 18-26%.
Using truck manufacturer’s performance charts is further discussed in the section on Selecting and Using Appropriate Truck Data in Design Guidelines (Gradeability and Retarding). What is clear and universal however, is the fact that rolling resistance, when acting against the load, will reduce truck speed and productivity, cause excessive fuel burn (one of the most significant costs associated with truck operations, as typically illustrated here), and reduce tyre and component life and increase maintenance costs.

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

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.
Haul Road Classification

A mine road network often comprises various roads, each with a specific function, some roads will be permanent roads, some semi-permanent, whilst others only temporary. Clearly, not all roads are ‘equal’ and thus any approach to design and management must be tailored to apply more resources to high volume, long-term and high cost-impact road segments across the network. Investing time, effort and resources on all mine roads is good, but the philosophy can be greatly improved by targeting that investment in the high cost-impact road segments across the network.

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.

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 and small wheel loads of 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 dependent 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, routine maintenance work, etc.) defeats the purpose of using these trucks in the first place.

**Approaches to Haul Road Classification**
A 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.

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 below, which shows Coopers (Snowden Consulting) models used to estimate the truck speed and fuel consumption variation with road grade and rolling resistance, in this case for flat-haul (0% grade) and ramp (10% grade) roads, to illustrate the impact of a change in rolling resistance from 2% to 5%.
For cycle time estimates from generic equations for haul truck speed estimation;

- Each 1% increase in rolling resistance above 2% base case increases cycle times by 20% on flat roads and 8% on ramp roads.
  - 2km ramp cycle from 13’06” → 15’24” mins (laden and return)
  - 2km flat haul cycle from 5’12” → 7’54” mins (laden and return)

- Haulage component of cycle time increases by approx 21%
For fuel consumption estimates from generic equations for haul truck speed estimation;

- Each 1% increase in rolling resistance above 2% base case increases fuel consumption by 25% on flat roads and 5% on ramp roads.
  - Ramp cycle consumption from 85→103 litres (laden + return)
  - Flat cycle consumption from 35→60 litres (laden + return)
- Total fuel cost increase of approx 28%

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 a haul road network. 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 here, 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 GVM t)</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 below. 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).

<table>
<thead>
<tr>
<th>HAUL ROAD CATEGORY</th>
<th>Max daily traffic volume (kt hauled)</th>
<th>Traffic type (largest allowable vehicle) GVMt</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

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 introduced previously.
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 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 a truck 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 previous 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 below. When using this information for design purposes, select the appropriate grade distance chart that covers total downhill haul, not individual segments of the haul.
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 dual tyre assembly, using:

- operating width,
- centreline front tyre width,
- centreline rear dual tyre width,
- type of tyre fitted and inflation pressure, and
- overall tyre width and/or laden contact area/radius (from tyre manufacturer data).
**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);

- effect of grade on any additional load transfer. Assume for a large RDT that approx. 1.6% additional load is transferred to a front axle, for every 1% of grade. Thus, at 10% descending grade for example, an additional 6.25% load is transferred to a (front) axle or vice-versa.

- 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.
# HAUL ROAD DESIGN AND CONSTRUCTION – TERMINOLOGY AND RESOURCES

## Learning Objectives

<table>
<thead>
<tr>
<th>Learning Objectives</th>
<th>Knowledge and understanding of;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Haul road terminology and layerworks typical of in-pit and ex-pit roads</td>
</tr>
<tr>
<td></td>
<td>The role of sub-grade (in-situ), fill, sub-base, base and wearing course in a road design</td>
</tr>
<tr>
<td></td>
<td>The correct sequence of layerworks for mechanistic and CBR cover-curve based design options</td>
</tr>
<tr>
<td></td>
<td>Basic material specification for combined sub- and base-layer used in the mechanistic design approach.</td>
</tr>
<tr>
<td></td>
<td>Resources required for mine haul road-building</td>
</tr>
<tr>
<td></td>
<td>Equipment requirements for road-building</td>
</tr>
<tr>
<td></td>
<td>Generic material classes encountered in mine road-building.</td>
</tr>
<tr>
<td></td>
<td>Simple selection criteria for generic classes of road-building material for layerworks construction.</td>
</tr>
</tbody>
</table>

**Application of;**

Planning of haul road route and the impact of in-situ materials encountered with basic resource requirements for construction.

**Calculate and predict;**

What road design component is typically implicated in illustrations of poorly performing sections of a haul road.
What Are We Designing and Building?

The roadway or road alignment has to provide a carriageway (or lanes) for trucks and also incorporate shoulders (for breakdowns, parked vehicles, etc.), berms and drainage.

In the diagram below, two options are shown:

- Typical in-pit road cross-section (LHS);
- Typical ex-pit (surface) cross-section (RHS).

Note the differing requirements in terms of berm placement at the edge of the pit road, and drainage features for both options. Definitions for the parameters shown above are;

<table>
<thead>
<tr>
<th>Formation width /Ramp/ Road Reserve</th>
<th>The formation is the working area in the road where earthworks are carried out. The width of the formation is directly related to the height of the earthworks above or below the natural ground or surface levels, the required batter slopes and the carriageway width.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carriageway</td>
<td>The portion of the haul road devoted to traffic, including road width and (if required) shoulders</td>
</tr>
<tr>
<td>Pavement</td>
<td>The pavement is that portion of the road placed above the subgrade to support and provide the running surface for traffic. It must provide a surface of acceptable ride quality with adequate skid resistance.</td>
</tr>
</tbody>
</table>

Working up through the layerworks (or courses) below the haul road, each has specific characteristics and function in the design and operation of the 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 to little ‘cover’ means that the sub-grade (or in-situ) will eventually deform and displace under the wheel loads of the trucks and the road will become very uneven, potholed and rutted. Because this layer is at the bottom of the road, it is expensive to repair this layer when problems arise. However, a design based on the appropriate Structural Design Specifications would accommodate various types of sub-grade or in-situ material and indicate 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 (on top of the sub-grade or fill). The sub-base provides a working platform upon which overlying layerworks can be compacted. A well-drained stable road base is one of the most important fundamentals in road design.

- When using a mechanistic structural design method for unpaved mine roads, the base and sub-base are combined in a single layer comprising selected blasted (hard) waste rock.

- If using a CBR-based cover-curve structural design approach, then the sub-base will comprise material somewhat ‘softer’ than the base, but ‘harder’ than the sub-grade or fill. These relative terms, ‘hard’ and ‘soft’ will be defined in more detail in the Chapter on structural design. With the CBR design method, a selected blasted waste rock layer can’t be used (or analysed).
Base
This is the layer immediately below the wearing course. It is important because it ‘protects’ the softer material below (in much the same way as the sub-base) from the loads imposed by 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 should follow the Structural Design Specifications.

Wearing Course/Sheeting
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', and as shown in this illustration, these poorly selected wearing course materials manifest different, but characteristic, problems; slippery when wet, excessive oversize and dustiness.

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 straight-forward - building the road according to the design is often easier too), the design process is split into a number of individual 'components' as was discussed in Chapter 1.

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, classification and operating 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 design and 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 briefly deflect a truck – and could create additional operational safety hazards too. Median (road centre or splitter) berm designs are also considered in under this design component.
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 sub-grade / in-situ. As will be seen later - water weakens the road layerworks 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, using a mechanistic design methodology (see Chapter 5), the base, placed directly on top of (compacted) sub-grade / in-situ must prevent this underlying material from undergoing excessive deformation as a result of the applied (truck) 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, maintenance of 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 associated with ‘fixing’ 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, as alluded to in the diagram below.
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), a simple example of which is shown below.

<table>
<thead>
<tr>
<th>DEPTH</th>
<th>LAYER</th>
<th>MATERIAL SPECIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0mm</td>
<td>Base</td>
<td>Selected blasted fresh quartzitic (eary) rock</td>
</tr>
<tr>
<td>300mm</td>
<td>Base</td>
<td>Blasted fresh, non-weathered, uncrushed or waste dump, maximum block size 30 x 80 x 500mm, 2% fines (&lt;20% passing 2mm).</td>
</tr>
<tr>
<td>1000mm</td>
<td>Sub-grade or in-situ</td>
<td>Compacted sub-grade</td>
</tr>
<tr>
<td>1000mm</td>
<td>Sub-grade</td>
<td>Do not water layer during compaction. Do not use sheeting.</td>
</tr>
</tbody>
</table>

Layerwork notes:
- Remove growth medium – cut or fill according to alignment. Exceptionally poor or clayey areas may require additional material removed and placement of a pioneer layer of selected blasted fresh or weathered waste rock prior to compaction.
- Rip sub-grade to a depth of 300mm.
- Recompact with a large vibratory roller until negligible movement seen under the roller. Min CBR 15.
- Import and end-tip selected unweathered blasted hard fresh waste rock of a maximum boulder size of ½ lift thickness and with fines limited to <20% passing 2mm. Doze into position in a single 800mm lift (for impact roller) or 2x400mm lifts for vibratory roller.
- Establish road prism at top of each lift, blind each lift if necessary with crusher run and compact with large vibratory/impact roller until negligible movement seen under roller. Do not water layer during compaction.
- Place correction layer if necessary (crusher run), compact and establish road prism and cross-fall or camber as required.
- Place sheeting as per specification.

For 20t vibratory roller compaction:
- End-raped to 2x400mm lift. Compaction to profile with 20t or larger impact roller. Do not water layer during compaction.
- For 25t impact/roller compaction:
  - End-raped 2x400mm lift. Doze layer to profile with 20t or larger dozer and compact until negligible movement seen under roller.

Obviously, resources are also required to make a road. These resources are typically:

- **time** - everything takes a certain amount of 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 complete 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, to some limited extent, but we can’t easily select the sub-grade / 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 sub-grade / in-situ and (if used in the design), the selected blasted waste rock base layers. The dozer must be able to shape the material 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 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 systems 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 layers – (especially for in-pit blasted material), an effect not easily replicated by a wheel dozer.
Compaction is critical to the success of a road-building project. 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 its density and ultimately its strength.

A large vibratory roller (230kN vibratory force) can assist in layer compaction - especially gravelly material, 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.

Preferably, a large impact roller should be used for layerworks (especially selected blasted rock base layer, if used) 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'.

Most contractors can supply impact rollers - however, it is also a useful piece of equipment for a mine to own and operate since it can be used to great effect in preparing waste dump roads, compacting the tip head, and blinding the bench floor in the loading area, which is always an area of potential tyre damage.

Grid rollers 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 specs, 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. (*Image courtesy of Synergy Positioning Systems Pty Ltd*).

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 nozzle 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 fit-for-purpose spray-bar is a better solution to effective watering than is a plate or drop spray – coverage is the key issue and no part of the road should be over-watered. Nozzles give finer coverage, less soaking and better watercart efficiency. Also – many roads react well to different spray ‘patterns’ and rates of application - this helps reduce potential damage to the road from excessive water (especially on ramps; it also prevents excessively slippery conditions). However, where traction or friction supply is problematic (poor wearing course material selection), this method of intermittent watering could lead to excessive wheel slip too – especially at the bottom of ramps where friction supply is at a premium for descending trucks). Light watering improves water cart 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.

These dosage and pattern spray systems ideally require a pump with an integrated vehicle speed-delivery control to maintain approx. 0.25-0.5litres/m² (0.25-0.5mm film thickness per m²) rates.

More advanced systems, using automatic control, geo-fencing etc. helps reduce overwatering on ramps and 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. Such a system is illustrated here, showing geofencing and the resultant road watering and application rate history recorded by the system. (Images courtesy of Australian Diversified Engineering (EcoSpray Systems)).
**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. *(Image courtesy of Grizzly Engineering Pty Ltd).*

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.

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**Materials for Road Building**

A road can be built above almost any (sub-grade or 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.

Layer characteristics will clearly vary from site to site, but there are some generic considerations that apply to the broad classes of materials themselves, as discussed below;
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 weaker, 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 uncompacted 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 (sheeting) 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 a mix of materials is required, the mix used is selected from material testing results. 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.
# Learning Objectives

<table>
<thead>
<tr>
<th>Learning Objectives</th>
<th>Knowledge and understanding of;</th>
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<tbody>
<tr>
<td></td>
<td>simplified geometric design process;</td>
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<tr>
<td></td>
<td>stopping distance and influence on geometric design;</td>
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<td></td>
<td>concepts of friction supply and demand as applied to geometric design of haul roads;</td>
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<td></td>
<td>sight distance concepts and the influence of blind spots;</td>
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<td>hazard and intersection sight distance requirements;</td>
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<td>procedure to determine optimal grade of a haul road;</td>
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<td>procedure to determine width of a haul road;</td>
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<td>how to select curve radius and associated requirements for super-elevation and run-in and –out;</td>
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<td>haul road drainage design and the use of crown or cross-fall;</td>
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<td>fundamental concepts of safety berm design.</td>
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<td><strong>Application of;</strong></td>
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<td>geometric design principles in both horizontal and vertical planes to assess haul road combined alignment.</td>
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<td><strong>Calculate and predict;</strong></td>
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<td></td>
<td>truck stopping and sight distance requirements for various geometric scenarios;</td>
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<td></td>
<td>curve radius and rates of super-elevation;</td>
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<td>optimum grade of a ramp road using truck speed-gradeability curves;</td>
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<td>haul road geometric design deficiencies using situational awareness.</td>
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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. 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. The steps are shown below.
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. Critically throughout the design process, reference is made to the local mine Traffic Management Plan or traffic rules, including priority rules, etc. since this information would also inform the design procedures, alignment and road layout decisions. Many of these additional considerations are dealt with in various Codes of Practice, for example; Worksafe Australia Roads & Other Vehicle Operating Areas Draft Code of Practice, DMP (WA) Mobile Equipment On Mines High Impact Function (HIF) Audit Part;

- Traffic management plans and traffic rules
- Mine access roads
- Road standards
- Separation and segregation of vehicles and pedestrians
- Restricted access exclusion zones
- Traffic movement around buildings, structures and service corridors
- Communications
- Lighting
- Traffic control signage
- Intersections
- Parking areas
- Road construction and maintenance

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.

**Stopping & Sight Distance Considerations**

Stopping distance requirements are a critical component of the geometric design process. Together with sight distance, they have a significant impact on the operational safety of a road. The truck manufacturer should ideally always confirm the distances required to bring a particular vehicle 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 be met and of course, what stopping distance is achieved in practice depends on the coefficient of longitudinal
friction supply (or skid resistance) of the road surface-wheel interface. Even if the braking system is capable of meeting or exceeding ISO 3450 requirements, that does not imply a vehicle will come to a standstill within that distance, as there are other factors in stopping distance calculations to consider.

In general, and including driver reaction times and importantly, brake system activation times, practical retard unassisted (emergency) braking distances can be determined from the equations:

\[
d_b = \frac{1}{2} g t_{p-r}^2 \sin \theta + v_o t_{p-r} + \frac{\left( g t_{p-r} \sin \theta + v_o \right)^2}{2g (U_{\min} \cos \theta - \sin \theta)}
\]

where;
- \(d_b\) = stopping distance (m)
- \(g\) = acceleration due to gravity (m/s²)
- \(t_{p-r}\) = driver reaction AND brake activation time (s)
- \(\Theta\) = grade of road (degrees) positive (+ve) downgrade
- \(U_{\min}\) = coefficient of longitudinal deceleration (friction supply)
- \(v_o\) = initial vehicle speed (m/s)

A further simplification yields;

\[
d_b = v_o t_{p-r} + \frac{v_o^2 - v_f^2}{2g (U_{\min} \cdot BE \cos \theta - \sin \theta)}
\]

where;
- \(v_f\) = final vehicle speed (m/s)
- \(BE\) = Braking efficiency (generally close to 100%)

or in alternative units form;

\[
d_b = \frac{V_o t_{p-r}}{3.6} + \left( \frac{(V_o)^2}{254 (U_{\min} - 0.01GR)} \right)
\]

where;
- \(V_o\) = initial vehicle speed (km/hr)
- \(GR\) = longitudinal grade (%), -ve upgrade, +ve downgrade.

A reliable first estimate for stopping distance is based on 'ideal' braking and vehicle conditions (dry road, good skid resistance, tyres in good condition and at recommended pressure, etc.), with \(U_{\min}\), the coefficient of longitudinal deceleration (a component of friction 'supply' in response to the 'demand' imposed by the decelerating haul truck), is generally taken as >0.25 and higher under...
certain favourable conditions). When conditions under braking vary (wet roads, poor and slippery wearing course, spillage, sub-standard tyres, etc.) a greater stopping distance would need to be considered. $U_{\text{min}}$, being $< 0.25$ (wet, soft, muddy, rutted road surface), but can be even lower in certain circumstances, e.g. ice on road, high clay content in wearing course, etc. In the above diagram, the shading represents the friction classifications (normal and warning levels 1-3) following the Tulloch/Stoker model.

In the illustrations above, note should be taken of the combined effect of changes to $U_{\text{min}}$, the coefficient of longitudinal deceleration and also the drivers’ and the vehicle reaction and brake activation time $t_p$. In each case, the purple line represents the ISO minimum stopping distance requirements of the braking system, which could easily be exceeded when conditions ($U_{\text{min}}, t_p, BE$) vary.

When friction supply falls below 0.25, haulage should be suspended until the road surface dries back to at least minimum friction supply value of 0.25. Typically, Australian site experience suggests between 0.4-0.8mm rainfall could induce changes in friction supply to below the desired threshold limit of 0.25. However, specification of a hard, aggressive larger size fraction in the wearing course or sheeting could extend operability of the road under wet weather conditions.

RSTS have conducted numerous ‘skid resistance’ tests if mine haul road sheeting materials to identify the change in skid resistance that occurs as a result of rain or watering on the road. The illustration below summarises a light- and heavy vehicle test (Image courtesy RSTS).
RSTS have developed a Haul Road Friction Classification Model (Tulloch/Stocker Model) shown below which indicates the critical levels of skid resistance that need to be maintained for safe haulage operations.

The guidelines indicate that when skid resistance or friction is maintained above 0.45, operation is safe (at least in terms of skid resistance and stopping distance requirements). Below that minimum threshold, three levels of warning are recognised; caution, potential hazard, and hazardous, for haulage operations. All four levels are shown superimposed on the previous illustration to indicate that in the case of this particular road, as water is applied, caution is required due to the drop in skid resistance available for mine trucks (from green to yellow area).

The actual stopping distance value adopted for design should be based on the vehicle with the longest stopping distance. The degree to which this distance will have to be increased will depend on the type of wearing course material, moisture content, climatic conditions, type of tyre, inflation pressures, load and vehicle speed also.

Friction supply cannot be continuously measured by a truck driver in-cab – only subjectively estimated from the ‘look and feel’ of the road. The safety issue is then if friction demand during braking is, for example, 0.25 and supply is 0.40, there is a significant safety margin. If however, the supply falls to 0.3, there is only a 0.05 margin of error and if steering is simultaneously required, this demands additional friction supply, so under these conditions there is little friction supply remaining to provide steering control.
Sight Distances

A driver needs to be able to perceive a road hazard or obstacle and decide on a course of action. The faster a vehicle is moving, the greater the distance ahead that the driver needs to both see and analyse. This is referred to as the sight distance, as measured from the operators’ cab, from the operator’s height of view.

The concept is illustrated above, in which (initially), approaching a horizontal curve, the bench ‘bull-nose’ limits the drivers’ sight distance round the curve. Note that at the point where the truck is located, the driver cannot see the hazard. At this point also, if the truck is to stop before encountering the hazard, the driver should apply the brakes. Obviously, this won’t happen since the drivers’ sight distance is restricted and by the time the obstacle is perceived, sight distance is much less than stopping distance, so the vehicle cannot stop in time to avoid the hazard.

**Sight distances must ALWAYS be in excess of the stopping distance.**

To fix the problem in this case, as shown in the lower diagram, a ‘layback’ can be applied, or the horizontal curve radius increased, to increase sight distance to at least the required stopping distance. 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 of inside lane R (m));

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

Length (L (m)) of vertical curves can be determined from consideration of the height of the operator’s eye level, in the cab \(h_1(m)\), an object of height \(h_2(m)\) (usually 0.15m to represent a prostrate figure in the road), SD the minimum stopping distance (m) and \(\Delta G\) the algebraic difference in grades (%);
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;

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

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

**Truck Operator Blind Spots**

In addition to sight distance requirements and the effect of road geometry on these limits, it must also be remembered that in a large mining truck, the operator does not have full 360° vision around the vehicle. This is referred to as blind-spots and will vary from machine to machine. When evaluating sight distance, and critically, intersection sight distances, it is important to consider whether or not the combination of truck positioning on the road, and the road geometry itself, will facilitate the required sight distance.

A typical driver-seat view from the cab of a large haul truck is shown alongside, highlighting the limitations to vision in the vicinity of the truck and especially the RHS offside position where the ROPS supports and other equipment on the truck terrace limit line of sight. This blind spot is shown below in a typical operators field of view diagram.
Illustrated above is a typical blind spot diagram for a large haul truck, from the blind area diagrams study (for selected mining vehicles), contract 200-2005-M-12695 by John Steele (Colorado School of Mines). The measurement approximates to ISO 5006, Earth-moving machinery – Operator’s field of view.

This information is valuable in determining the alignment of the haul road and anticipating where, when negotiating the network of roads, driver blind-spots may exist.
Vertical Alignment Issues

Vertical alignment is primarily a function of pit geometry and the associated ramp gradients. Maximum gradients should be based on gradeability considerations for the type (electric or mechanical drive) and model of trucks operated. Each vehicle has a specific speed-rimpull-gradeability characteristic which is most often related to either total or effective resistance (grade ± rolling resistance) or simply grade (in which case, rolling resistance is added or subtracted as appropriate). Additionally, the brake performance characteristics also need review – although on the return downgrade journey, braking capacity of unladen trucks would allow high speeds, practically it is often necessary and desirable to limit unladen or laden descent speeds according to road conditions, rather than limit purely by brake capacity.

Typical standard brake and retarding configurations for a 220tonne payload class mechanical drive haul truck with 5.1kW engine power (SAE)/tonne GVM are shown below LHS. In the design of the ramp gradient, limiting drive to 1D or 2D would imply a total resistance of 13% and 11% respectively, equating to a grade of typically 10% and 8% if a rolling resistance value of 3% were assumed. However, a slight increase in rolling resistance or grade above stated values would cause the truck to operate the next lower speed range (torque converter drive) which may accelerate damage to engine and drive-train components as a result.

In the case of a similar sized and powered electric drive truck (4.8kW engine power (SAE)/tonne GVM, 18-element blown retarder 7-step grid) as shown above (RHS), there is a theoretically higher limit to gradeability, apart from the traction and braking limitations imposed by severely steep grades.

For downgrade unladen or laden travel, truck manufacturer braking/retard design charts are used to determine theoretical descent speed limits (so that braking capacity is not exceeded. However, as noted, practically, further speed limits may need to be posted to ensure safe operation of the road, etc. Using the previous two examples, at both 8% and 10% grade (5% and 7% effective down-grade) posted safe ramp speed limits should be applied for both laden and unladen descent, for both mechanical and electric truck drive options. For laden or unladen descent, mechanical drive trucks should operate in 4th and 3rd gears respectively to ensure braking does not exceed brake cooling capacity. This data is based on 32°C ambient temperature at sea level with recommended tyres and...
OEM recommended gross and unladen vehicle weights. This requirement will vary with the truck model and brake options selected.

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

- a long shallow ramp (low grade) - (truck is fast because effective resistance is low, but ramp is long - hence long travel times)
- a short steep ramp (high grade) - (truck is slow because effective resistance is high – but ramp is shorter - hence long travel times)

In the example here, a simulation was used to determine optimum grade curve for a particular truck with 2%, 3% and 4% rolling resistance (RR) added to the grade resistance. The truck travel time is minimum at approx. 10% grade (@2%RR), about 310s for a 100m vertical rise. 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.

Similar effects are seen on the (unladen) down-grade haul, but in this case truck speed is related to braking or retard option fitted and length of haul. The travel times shown here are based on maximum speeds at 70% of retard capacity and do not consider any over-riding speed restriction or local requirements. Rolling resistance does not play a significant role in varying the down-grade unladen travel times and the optimum 14% grade.

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 diagram alongside, 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).
Horizontal (Longitudinal) Alignment Issues

Width of Road

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 in use at a site will determine the road width.

<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.

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.

A typical design for a category I road running 220t class haul trucks is shown below (with optional median berm, as discussed later).
Minimum in-pit haul road/ramp reserve in this example is 48m, from outslope bench crest to inslope bench toe. This width comprises:

- Outslope batter offset (crest erosion, blast damage, etc.) 2.3m
- Outslope berm (refer berm design notes) 4.7m
- Outslope trapezoidal drain (refer drainage notes) 4.0m
- Outslope shoulder 2.0m
- Road width (3.5W @ W=8.3m) 29.0m
- Inslope shoulder 2.0m
- Inslope trapezoidal drain (refer drainage notes) 4.0m

Batter offset can be reduced/omitted where crest damage and/or water run-off erosion is minimised and blasting practices reduce potential crest instability/damage. When shoulders are omitted, if vehicles park or become unserviceable on road, temporary road traffic control will be required for safe traffic operations whilst removing obstacle. No inslope berm is used here unless embankment batter slopes exceed 1V:4H, road side drop-offs are greater than 0.5m or there is an unacceptable risk of collision between vehicles or road side obstacles.

**Turning Circle of Large Haul Trucks**

The starting point for any horizontal curve design would be from consideration of the turning circle of the largest, or limiting, vehicle intended to use the road. The turning path of a typical 2-axle rear-dump haul truck is based on the outer front (steering) wheel path following a circular arc at under 16km/h. GVM, tyre and suspension characteristics have a negligible effect in low-speed turns. However consideration should be given to the swept path or required additional clearance due to the combination of turning circle and innermost and outermost projections of the vehicle body when negotiating a curve and any off-tracking, as shown below.

The following definitions apply:

Turning circle clearance radius (machine clearance diameter ISO 7457:1997), (Turning radius – wall-to-wall SAE J695:2011) - Radius of the smallest circle which will enclose the outermost points of projection of the machine and its equipment and attachments when it executes its sharpest practical turn.
Turning circle radius (ISO 7457:1997) - Radius of the circular path described by the centre of tyre contact when the wheel describes the largest circle when the machine is executing its sharpest practicable turn.

Turning centre - Point about which all turns of constant radius are made. For ideal steering, free of tyre scrubbing, the extended axis of all wheel spindles passes through this centre. In the case of dual assemblies in which the axles are constrained to parallelism, the turning centre is assumed to fall on a line parallel to and midway between these axle centrelines.

Turning diameter – double the turning circle radius described above.

Off-tracking refers to the difference in the centre-point paths of consecutive axle paths which are not coincident and where an offset exists between axle paths. The amount of off-tracking (which when negative implies tracking inward towards turning centre), that will affect the swept path (difference between inner and outer clearance radius) can be determined from;

\[
D_{ot} = -R + \sqrt{R^2 - WB^2}
\]

where;

\begin{align*}
R & = \text{Radius of curve (m)} \\
WB & = \text{Wheel base of truck (m)}
\end{align*}

For example, off-tracking for a 220tonne class of RDT is approximately at a maximum of -1.1m for the minimum turning circle clearance radius of 16.5m.

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, haul costs and also tyre costs.

The dual tyres on drive axles are especially prone to wear going around tight curves. A switchback with an inside depression dug from tyre slip is common and if the depression exposes road base, these rocks will damage the tyre, as shown below. 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:

\[
R = \frac{v_0^2}{127(U_{\text{min}} + e)}
\]

Where;

\( e \) = super-elevation applied \((\text{m/m width of road})\)

\( U_{\text{min}} \) = coefficient of lateral friction supply

\( v_0 \) = vehicle speed \((\text{km/h})\)

\( U_{\text{min}} \), the coefficient of lateral friction supply, is generally taken as 0.0 (where no measured data available) to 0.25. Where the pit layout requires a tighter radius than the minimum radius indicated at a particular truck speed, speed limits need to be applied. Care should also be taken when assuming a value for the coefficient of lateral friction – many of the factors that influence the coefficient of longitudinal deceleration also apply to this coefficient too.

Switchbacks should be designed with an inside ramp string radius to give a minimum inside tyre path radius of at least 150% of the minimum turning circle clearance radius. Width of switchback including inslope and outslope berms and inslope small trapezoidal drain will vary with road width design as described previously. Outslope berms can be omitted if safe to do so but the inslope berm should be built to assist the truck drivers sighting alignment through the switchback. Divider or median berms should be used where the possibility of truck sliding exists.

Switchbacks should be designed ideally at no more than 3% gradient for at least the semi-circumferential length of the switchback with super-elevation applied throughout the curve. However, high rates of road wear and degradation can be anticipated on and leading down to these features due to the tight radius curve, scouring and vehicle braking requirements on approach. If designed on grade, a maximum 10% gradient on the inside windrow curve radius should be maintained and speed limits should be applied well in advance of the switchback for downgrade vehicles. Drainage should be led off the road on the upslope side of the switchback since drainage in the neck of the switchback is limited and problematic. Drainage on the outside of the curve is not required when super-elevations are applied. A typical design is shown below (based on a given truck width and associated drainage and safety features).
Curve Super-elevation (Banking)

Super-elevation refers to the amount of banking applied from the outside to the inside of a curve to allow the truck to run through the curve at speed (generally when speed exceeds about 15km/h). Ideally, the outward centrifugal force experienced by the truck should be balanced by the lateral friction supply between tyres and road. Super-elevations should not exceed 5% -7%, unless high-speed haulage is maintained and the possibility of sliding minimized. In the illustration alongside, perspective has been adjusted to better illustrate super-elevation.
In this illustration, with no super-elevation applied in the curve, the truck centrifugal forces are unbalanced and tyre positions 1, 3&4 carry higher loads, leading to potential tyre and strut/chassis stress issues (as well as damage to the road surface).

<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></td>
<td>15</td>
</tr>
<tr>
<td>50</td>
<td>0.035</td>
</tr>
<tr>
<td>75</td>
<td>0.025</td>
</tr>
<tr>
<td>100</td>
<td>0.020</td>
</tr>
<tr>
<td>150</td>
<td>0.020</td>
</tr>
<tr>
<td>200</td>
<td>0.020</td>
</tr>
<tr>
<td>300</td>
<td>0.020</td>
</tr>
<tr>
<td>400</td>
<td>0.020</td>
</tr>
<tr>
<td>500</td>
<td>0.020</td>
</tr>
</tbody>
</table>

The Table shows typical super-elevation rates based on speed of vehicle and radius of curve with $U_{\text{min}}$ (coefficient of lateral friction supply) set to zero. 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 (crown), 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.

![Diagram of run-out (development of super-elevation)](image)

Runout lengths vary with vehicle speed and total cross-fall or camber change and can be estimated from the equation below where where $CS_x$ is the maximum change in cross-fall per 30m-road length and $v_0$ the speed of the truck (km/h).

$$CS_x = 15.65 - 5.67 \log_{10}(v_0)$$

Generally, 0.02m/m/10m length of road is a good rule of thumb for the maximum run-out rate that should be used. Run-out can also be incorporated in a mine road design by 'eye' or 'feel' rather than by calculation – if the curve and approaches feel safe and comfortable in a light vehicle, it will also be suitable for a large mine haul truck. 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.

Cross-fall, Crown or Camber

A cross-fall, (cross-slope), crown (or camber), as shown in this illustration, 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. On ramps roads, a reduced cross-fall, crown or camber should be used. If absent, water will only run down the ramp and not down and off to side drains. If water doesn’t run off the road, it will eventually gather enough speed to cause serious erosion of the wearing course and drains at the low-point of the ramp.

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, 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 cross-fall down-slopes meet, a table drain or drainage ditch must be provided. It is critical to ensure that the drain forms part of the road formation and is well compacted, to prevent run-off water from simply penetrating through the drain and into the layerworks.

A camber (crown) or cross-slope of 2 to 3% is ideal, providing adequate drainage without incurring adverse truck tyre and strut loading conditions. A preference may exist for cross-slopes due to the envisaged equalized load sharing and reduced tyre scrub. A cross-slope should be used with caution, when the slope falls towards the outside of the bench (crest or outslope position) as opposed to the bench toe side. Where a camber or crown is selected - and where this leads to the possibility of trucks sliding in the direction of the bench crest or outslope, or towards a large vertical drop - large deflection berms /windrows should be placed at the road edge.

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.
Intersection Design

The predominant type of accident that occurs at intersections of mine roads is due to haul truck and light vehicle interactions in and around the intersection. A key issue is both vehicle misalignment in the intersection and the blind spots of the truck (especially over the terrace to the RHS of the truck). Ideally, the angle at which intersecting roads meet should be between 70-90°. In the diagram alongside, a poorly aligned intersection is shown, both from the horizontal and vertical alignment perspectives.

Avoid intersections near the crest of vertical curves or sharp horizontal curves (with high super-elevation), nor placing an intersection on the inside of a horizontal curve. Intersections should be as flat as possible with sight distances being considered in all four quadrants, and 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. The use of splitter islands on the approach to an intersection will help channelize traffic and reduce the tendency to cut corners. It will also assist in demarcating ‘no overtaking’ areas on the approach to an intersection.

Sight distance requirements at intersections, as originally determined following RSTM, need to be considered from the perspectives of;

- Approach sight distance; the truck operator should have adequate distance to assess, react (and if necessary), stop the truck before entering the intersection areas of potential conflict;
- Minimum gap sight distance; the distance required for truck traffic to join the (main ramp, for example) haul road without impeding traffic approaching the intersection on the main ramp road;
- Safe intersection sight distance; the minimum design standard and should provide enough distance for a truck operator on the ‘main’ haul road to assess, react and (if necessary), stop the truck should a potential conflict arise with traffic entering from the intersection.

A proposed layout is given below, following an original scheme proposed by RSTM;
Roundabouts, as an alternative to more complex multiple entry- and exit-road junctions, should be positioned in safe locations away from horizontal and vertical alignment changes.

Traffic splitter islands should be installed to slow speeds of vehicles entering the roundabout with Keep Left signs installed at the end of islands. Haul truck tyres painted white may be used as an alternative – but note should be taken of the increased road hazard risk associated with this option.

The design speed of the roundabout is determined from the smallest radius along the fastest allowable path. The smallest radius usually occurs on the circulatory roadway as the vehicle curves to the right around the central island. However, it is important when designing the roundabout geometry that the radius of the entry path (i.e. as the vehicle curves to the right through entry geometry) not be larger than the circulatory path radius and ideally, to maintain sight distance and avoid blind-spots, approach the circulatory road at close to right angles. Design software such as ARNDT can be used to develop a design suitable for the road junction geometry and vehicles using the roads.
Combined Alignment
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 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** vegetation, roadside furnishings or excessively high splitter islands that would otherwise eventually limit sight distances in any of the four quadrants required, especially in the case of other road users. Take care to locate signage so as not to obstruct sight lines.
- **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

The function of a 'crest' or road-edge berm /bund or windrow can either be considered as an 'arresting' device, or as a 're-directing' device for misaligned trucks. A berm will not effectively stop trucks (especially high speed laden or unladen trucks) from leaving the road. At best, they will provide limited deflection and warning to the driver that the truck path needs correcting. The material comprising the berm and its 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. Also note that with this ‘re-directing’ approach, the truck itself may become a hazard on the road when it is redirected by the berm. For large haul trucks, the berm height should be at least 66% of the truck wheel diameter. A typical design for a 930E haul truck is shown below – primarily for re-directing as opposed to arresting. With the latter design, a larger outslope batter offset may be required if the truck straddled the berm during deceleration.

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 (except for junction splitter islands – reduce height of berm so as to not restrict intersection sight). 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 (cross-fall drainage will not be appropriate – a crown must be used) should all be additional considerations. Note that this discussion relates primarily to roadside and median berms, the design principles for tip head berms are not addressed here.

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, direction of drainage and run-off and the requirements and 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 layer works. 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. Ideally, drains should be located in undisturbed material rather than fill material. 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. Side slopes of drains are typically 3H:1V adjacent to road shoulder and should not exceed 2H:1V on the outslope except in extremely restrictive conditions. The outslope will vary with the material encountered. In rock it may approach a vertical slope; in less consolidated material, a 2H:1V slope or flatter.

Drains should be a minimum of 0.3m deep (unlined) and should be regraded when depth has been reduced by 50%. Where flow capacities require a deeper/wider drain, which may constitute a traffic hazard, the outslope berm should be placed adjacent to the haul road shoulder and be cut-through at 6m intervals and/or low points to allow water to drain off the road.

Any drains must be designed to adequately handle expected runoff flows determined by the mine hydrologist/hydrogeologist, 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. Ditch lining is a function of road grade and in-situ material characteristics:
- At 0% to 4% grade the drain may be constructed without the benefit of a liner except in extremely erodible material such as sand or easily weathered shale silts and clays. Spray-seals should be applied to drain and side slopes.

- At grades over 5%, the lining should consist of coarse, crushed waste rock (riprap) placed evenly on both sides to a height no less than 0.3m above the maximum depth, and depending on depth and width of drain, a minimum freeboard of 100mm should be used where feasible.

Rock lining (riprap) size depends on flow velocity, drain bed slope and rock density. For a typical crushed rock, 2.6t/m$^3$ may be assumed. Assuming a uniform flow velocity the following sizes ($d_{50}$) for angular (crushed) riprap should be used;

- Gradients (bed slopes) <5%
  - For flow velocities ($v$)(m/s) $1.5>v>0.5$ : $d_{50}=100$mm
  - $2.0>v>1.5$: $d_{50}=200$mm
  - $2.5>v>2.0$: $d_{50}=300$mm
  - $3.0>v>2.5$: $d_{50}=400$mm

- Gradients (bed slopes) >5%
  - For flow velocities ($v$)(m/s) $1.5>v>0.5$ : $d_{50}=100$mm
  - $2.0>v>1.5$: $d_{50}=300$mm
  - $2.5>v>2.0$: $d_{50}=400$mm
  - $3.0>v>2.5$: $d_{50}=500$mm

Note that where large riprap is required, depth and width of drain may need to be increased to maintain design capacity.

Minimum thickness (T) of rock lining is recommended as;

- $1.4d_{50}$ when $d_{50}/d_{90}>1$
- $1.6d_{50}$ when $d_{50}/d_{90}>0.8$ (upper limit of quarry rock)
- $1.8d_{50}$ when $d_{50}/d_{90}>0.67$
- $2.1d_{50}$ when $d_{50}/d_{90}>0.5$ (lower limit of quarry rock)

Velocity of flow should be no less than 0.5m/s to prevent excess sedimentation. Silt traps or combined energy dissipaters should be considered when flow velocity typically exceeds 4.5m/s.

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.

Minimum culvert internal diameter is 600mm and preferably 900mm for ease of maintenance.
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 typically 500mm over the pipe is required for the strongest RCP (Class 10) for most large truck applications, increasing with lower class pipes 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.

A suitable headwall should be constructed from 2x1x1m gabions and 2x1x0.30 Reno mattress. Gabions are rectangular woven wire mesh baskets filled with rock to create flexible, permeable structures for erosion protection. Reno mattresses are thin, flexible rectangular mesh cages filled with rock to limit movement during high-flow conditions. Because of their flexibility, a Reno mattress is used mainly for scour protection and embankment stability in channel linings.

Under extremely high rainfall intensities, rolling dips (broad-based dips or oblique drains) should be considered on all roads to intercept water flowing down any ramp road. A rolling dip is generally constructed at the top of the ramp, prior to commencing descent, if there is possibility of water entering the ramp from an intersection with other (through) haul roads, and further rolling dips should be constructed at 300-600m intervals on the ramp to catch and disperse surface water (and inslope drain flows if necessary) to the outslope.

In most cases, rolling dips should be angled at 10-20° from perpendicular to the road, to the outslope, with a 2-4% outslope (similar to crossfall applied) and be long enough to allow safe passage of vehicles (at least 50m). A 3-6% reverse slope should be used. Rolling dip angles in excess of 20° from perpendicular will enhance water flow velocity and minimise sedimentation but can cause excessive vehicle racking and will also increase cycle times due to the requirement to reduce speed on approach. A stockpile of sheeting material should be located on the downslope side of the dip for repair and maintenance of the dip, which may be subject to scour under high intensity rainfall events.
## Learning Objectives

<table>
<thead>
<tr>
<th>Learning Objectives</th>
<th>Knowledge and understanding of;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design of layerworks for mine roads;</td>
</tr>
<tr>
<td></td>
<td>The role and importance of compaction in mine road construction;</td>
</tr>
<tr>
<td></td>
<td>CBR-based mine road methodology design and its limitations;</td>
</tr>
<tr>
<td></td>
<td>The fundamentals of the mechanistic approach to mine road design;</td>
</tr>
<tr>
<td></td>
<td>Data requirements for the CBR and mechanistic structural design methods;</td>
</tr>
<tr>
<td></td>
<td>Use of the DCP and material classification charts to derive estimates of layerworks strength.</td>
</tr>
<tr>
<td></td>
<td><strong>Application of;</strong></td>
</tr>
<tr>
<td></td>
<td>AASHTO and USCS classification systems to estimate layerworks material CBR and effective elastic modulus values;</td>
</tr>
<tr>
<td></td>
<td>CBR design charts for the specification of mine road layerworks thicknesses;</td>
</tr>
<tr>
<td></td>
<td>Mechanistic design charts for the specification of blasted waste rock base layer thickness.</td>
</tr>
<tr>
<td></td>
<td><strong>Calculate and predict;</strong></td>
</tr>
<tr>
<td></td>
<td>CBR cover-curve design layer thicknesses for a given wheel load and layerworks material strengths;</td>
</tr>
<tr>
<td></td>
<td>CBR cover-curve design layer thicknesses ESWL corrections;</td>
</tr>
<tr>
<td></td>
<td>Required road design category, using life of road and traffic volumes, for a mechanistic design methodology.</td>
</tr>
</tbody>
</table>
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 sub-grade (in-situ) material strengths and structural thicknesses.

The California Bearing Ratio (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 or 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 (sub-grade) and the compaction and layerworks or (selected) blasted waste rock layer (as combined sub-base and 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 and/or possibly deform 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 sand) 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 its ideal size - maximum block size about 2/3rds of the layer thickness.

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.
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 for mine roads, developed by Kaufmann and Ault (USBM) from roads and airfields methodologies, 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, road 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 and any layer to layer increase in CBR limited to about 200-250% of the preceding CBR value.

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 similar approaches to 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 (single front and rear dual-wheel axle) 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 cover is used in this chart as opposed to the original sub-base thickness criteria.

Conventionally, the role of the sheeting or wearing course is not considered in the CBR cover-curve design approach. However, with mine haul roads, due to the recommended design thickness of this layer (200mm) and the regular maintenance the roads are subjected to, the omission of this layer maybe a somewhat conservative assumption.

The following equation can alternatively be used to estimate the layer thickness ($Z_{CBR}$ (m)) required for a material of California Bearing Ratio (CBR %);

$$Z_{CBR} = \frac{9.811tw}{P}[0.104 + 0.331e^{(-0.0287tw)}] \left[2 \times 10^{-5}\left(\frac{CBR}{P}\right)^{0.415+P \times 10^{-4}}\right]$$

Where $t_w$ is the truck wheel load (metric tonnes), $P$ is tyre pressure (kPa) and CBR is the California Bearing Ratio of the layer material (%).
Originally, the truck 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 \( Z_{ESWL} \) (m) more reliably as:

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

NOTE when applying the above formulae to a design determination, due to the estimation characteristics of the formulae, a more realistic final layer thickness is found by subtraction of the sum of preceding layers from total cover requirements. The final design would then incorporate the sheeting layer above the total cover thickness determined from the previous equations or charts below.
In using this technique, consider the ‘cover’ required for a 384tonne GVM haul truck with a 64.3tonne wheel load. If the sub-grade CBR is 5% (approx. \( E_{uf} = 50\text{MPa} \)), the pavement thickness required is 1420mm. If the sub-grade were ripped and recompacted to form a lower sub-base layer of CBR16%, pavement cover required (above ripping and recompacted sub-grade) is now 688mm so 
\( (1420 - 688) = 732 \) mm layer thickness is required (most likely as two lifts). Placing an upper sub-base of CBR=28% results in a cover requirements of 443mm so (688-443) = 245mm layer thickness, following which a CBR=60% base is placed, which requires cover of 197mm and thus 246mm layer thickness. Ideally, a yet harder material is required, CBR>80% and would for design purposes be specified to 197mm (practically rounded to 200mm) depth, following which a sheeting layer of 200mm would be placed.

Using an ESWL approximation of 1.2xwheel load (77t), if the sub-grade CBR is 5%, the pavement thickness required is 1922mm. Proceeding as before, a ripped and recompacted lower sub-base of thickness 1066mm is required, overlain by a 315mm layer of upper sub-base, 297mm layer of lower base and 243mm upper base layer.

As the total and layer thicknesses shown above illustrate, construction can become costly where weak materials and high wheel loads are encountered. Weak materials deeper in the pavement are especially prone to high stress and strain due to the interaction and overlap of these effects at depth. However, when multi-layered roads are considered in conjunction with a base layer of selected blasted waste rock, a mechanistic approach is more appropriate and often cheaper to build.
Also, since the CBR methodology cannot adequately account for the high strength offered by this type of layerworks, a mechanistic approach to structural design is more often suitable. However, it does require considerably more data than the CBR-based design charts discussed above.

**Mechanistic Structural Design Method**

Using a mechanistic design methodology, the specification of the layer thicknesses and compaction is based on limiting load-induced strains in the softer sub-grade/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, sub-grade or fill such that the road will perform satisfactorily over its design life. Typical limiting sub-grade vertical compressive strain values from various sources are summarised in the figure below.

**Estimation of limiting sub-grade layer vertical compressive strain values for mine haul road construction**

![Diagram showing limiting sub-grade layer vertical compressive strain values](image)

**Notes**

1. Based on acceptable structural performance of road and maximum deflection under fully laden rear dual, where Performance Index (PI) varies from:
   1. Adequate but fairly maintenance intensive,
   2. Good with normal maintenance interventions,
   3. Outstanding with low maintenance requirements.

2. For Tannant & Regensburg models, design life based on 220tonne payload truck, load cycles determined using two axles and Performance Index of 2 used.

<table>
<thead>
<tr>
<th>Haul Road Category</th>
<th>Typical Description</th>
<th>Traffic Volumes &gt;100kt/day</th>
<th>Traffic Volumes &lt;100kt/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category I</td>
<td>Permanent life-of-mine high volume main hauling roads and ramps in- and ex-pit. Operating life &gt;20 years</td>
<td>900</td>
<td>1 500</td>
</tr>
<tr>
<td>Category II</td>
<td>Semi-permanent high volume ramp roads in-pit or waste dump access roads. Operating life &gt;10 years</td>
<td>1 500</td>
<td>2 000</td>
</tr>
<tr>
<td>Category III</td>
<td>Short term medium - to low - volume in-pit bench access, ex-pit dump, or ramp roads. Operating life; &lt;5 years (&gt;50kt/day) or &lt;10 years (&lt;50kt/day)</td>
<td>2 000</td>
<td>2 500</td>
</tr>
</tbody>
</table>

**Range of Maximum Permissible Vertical Elastic Strains (microstrains)**

<table>
<thead>
<tr>
<th>Haul Road Category</th>
<th>Traffic Volumes &gt;100kt/day</th>
<th>Traffic Volumes &lt;100kt/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category I</td>
<td>900</td>
<td>1 500</td>
</tr>
<tr>
<td>Category II</td>
<td>1 500</td>
<td>2 000</td>
</tr>
<tr>
<td>Category III</td>
<td>2 000</td>
<td>2 500</td>
</tr>
</tbody>
</table>
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.

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 provide adequate service over its design life. The Figure summarizes the layered elastic model and data requirements.

Once the strain criteria are selected, 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. OEM data should be accessed to determine the load geometry, generally based on a single dual assembly for the appropriate laden condition of the truck. The dual wheel centre to centre spacing \( S_d \) (m) is required:

\[
S_d = (Overall\ rear\ dual\ tyre\ width - Centreline\ rear\ dual\ tyre\ width) - Tyre\ width
\]
In the absence of specific geometric details, $S_d$ (m) can be estimated using the tyre width and a dual clearance of approx. 0.2-0.4m. Alternatively, the equation below approximates $S_d$ for most models of large rear dump mining trucks (RDTs);

$$S_d = \frac{GVM}{12.67GM^{0.512}}$$

Tyre pressures are required, based on OEM specifications, generally 600-900kPa in most cases.

Often, manufactures will accommodate a 10:10:20 overload rule which implies that no more than 10% of truck loads should exceed 10% of payload and none may exceed 20%.

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, and CIRCLY6. Irrespective of the solution software used, the theoretical approach is similar. However, CIRCLY6 is the most intuitive to use and usefully solves for layer thickness when a maximum permissible vertical strain value is specified.
Typical results would include an assessment of modelled versus critical strains at the sub-grade boundary, together with an indication of maximum surface deflections, associated with the proposed/existing design(s) and truck type(s). The table below shows results for a CAT793D running on CATI-III roads and the associated selected blasted waste rock layer thickness for each.

The table below shows results for a CAT793D running on CATI-III roads and the associated selected blasted waste rock layer thickness for each.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
<th>Thickness (mm)</th>
<th>$\varepsilon_v$ (microstrain)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/C</td>
<td>Wearing course</td>
<td>3 000</td>
<td>200</td>
<td>2.1</td>
</tr>
<tr>
<td>Base</td>
<td>Selected dump rock</td>
<td>3 000</td>
<td>846</td>
<td>3</td>
</tr>
<tr>
<td>Sub-grade</td>
<td>Clay CBR=5 (Rigid below)</td>
<td>3 000</td>
<td>900</td>
<td>1.7</td>
</tr>
</tbody>
</table>

The effective modulus of elasticity ($E_{eff}$) (resilient modulus) and Poisson’s ratio ($\nu$, typically 0.35) define the layerworks material properties required for computing the vertical strains ($\varepsilon_v$) 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 either infinite in depth, or limited to depth of weathering, or solids, as appropriate.

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 below 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.

Alternatively, resilient modulus ($E_{eff}$) values for the various pavement layer materials can be based on AUSTROADS and QDMR $E_v$ and California Bearing Ratio (CBR) relationships.

\[
E_{eff} = \begin{cases} 
21.1CBR^{0.64} & \text{QDMR (CBR<15)} \\
19CBR^{0.68} & \text{QDMR (CBR>15)} \\
10CBR & \text{AUSTROADS 1992 (CBR<15)} 
\end{cases}
\]
A slightly more conservative (lower-bound) estimate is generated from the TRL/AASHO (Powell, 1984) model, as shown in comparison in the Figure above.

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

| CBR (%) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 15 | 20 | 30 | 40 | 60 | 80 | 100 |
|---------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|
| Modulus ($E_{eff}$)(MPa) | 10 | 14 | 21 | 28 | 35 | 41 | 55 | 69 | 104 | 138 | 207 | 278 | 345 | 414 |

<table>
<thead>
<tr>
<th>AASHTO Soil Classification</th>
<th>A-1-b</th>
<th>A-1-a</th>
</tr>
</thead>
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<tr>
<td>A-2-7</td>
<td>A-2-6</td>
<td>A-2-5</td>
</tr>
<tr>
<td>A-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-5</td>
<td>A-6</td>
<td>A-7-5</td>
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<td>A-7-6</td>
<td>A-7-5</td>
<td></td>
</tr>
<tr>
<td>CH</td>
<td>MH</td>
<td>CL</td>
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<tr>
<td>Unified Soil Classification</td>
<td>SP</td>
<td>SW</td>
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<tr>
<td></td>
<td>SW-SM</td>
<td>SP-SC</td>
</tr>
<tr>
<td></td>
<td>SC</td>
<td>SM</td>
</tr>
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<td>GP</td>
<td>GP-GC</td>
</tr>
<tr>
<td></td>
<td>GP-GM</td>
<td>GC</td>
</tr>
</tbody>
</table>

The modulus value adopted for the selected blasted waste rock base layer is typically 1500-3000MPa and was determined from back-calculation from field test data. This value is comparable to 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, material of marginal quality or lifts excessive, this value should be reduced to 1500-2000MPa. This would be more typical of a rubblized PCC base layer, to which a well compacted and interlocked blasted waste rock layer would correspond.
Material Selection, Evaluation and QAQC – Layerworks

Selected Blasted Waste Rock Layer

The base layer selection and compaction applies to material consisting predominantly of blasted fresh rock which, due to the mechanical interlocking of the rock, cannot be tested for compaction effectively by the methods normally used for soils and gravels.

Minimum specifications for the source material chosen for this layer include;

- uniaxial compressive strength in excess of 100MPa,
- not containing weathered rock, clay or soil with no more than approximately 20% -2mm material (AS1141.11.1) and predominantly freely draining material when placed and compacted,
- an LA_b abrasive index of no more than 30% (AS1141.34),
- have no more than 1% weak particles (AS1141.32),
- have a minimum particle density of 2.0t/m$^3$
- the largest block size is ideally $\frac{2}{3}$ lift thickness which equates to between 200-300mm maximum. Larger rock is difficult to compact and forms a high spot in the layer surrounded by a ring of soft uncompacted material.

Construction specifications should state that the layer is end-tipped, dozer shaped to road prism in lifts not exceeding 300mm for 230kN vibratory roller compaction or 500mm for a (minimum 25kJ) impact roller then rolled until negligible movement is seen under the roller. For an impact roller 10-15 passes should generally be sufficient per lift. The layer can be blinded with 75mm crusher run to finish if required.

It is recommended that construction techniques be developed based on method specification, using at least a 300m section of trial road in which at least 90% of consecutive tests satisfy or exceed the performance standard specified. Frequency of tests will depend on site supervision, quality and variability of material source:

- for layerworks materials, one test per 3,000m$^3$ of construction or 250m intervals.

For in-situ/subgrade materials, QAQC testing should confirm;

- minimum in-situ/subgrade CBR as per structural design specification after rip and recompact. CBR should extend to at least 300mm depth below top of in-situ/subgrade. Alternatively a light-weight deflectometer can be used to confirm that the E-modulus meets minimum equivalent.

Frequency of tests will depend on site supervision, quality and variability of subgrade along road centreline:

- for in-situ/subgrade materials, tests at 200m intervals along centre, left and right carriageway outer wheel paths.
DCP Evaluation of Layerworks Materials
Since each mine road design situation varies, it is necessary to gather data concerning the strength of the in-situ, sub-grade and layerworks materials 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 $E_{eff}$ 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 below.
Individual road layers, their thickness and CBR values can thus be determined, where there is a significant change in the CBR values recorded against depth. In the illustration below, three layers are recognised; wearing course CBR100 to approx. 150mm depth, base CBR30 to 450mm depth and sub-base CBR10 to 900mm (max depth of DCP).

In this instance, the poorly performing section of road was as a result of the extremely soft material used as a base layer in this location, coupled with inadequate layer thickness – although under these circumstances the wearing course or sheeting looks suspect – no wearing course, even if well selected and compacted, is going to perform as required when there is inadequate support from the layerworks.
CBR vs Mechanistic Design Methodologies
As was mentioned earlier, the CBR design methodology is empirically derived from concepts developed for much smaller wheel loads and subsequently modified further for larger aircraft gear loadings. It is primarily suited to an initial design review in cases where no selected blasted rock layer is used in the design. Where a selected blasted rock layer is adopted, the mechanistic design process is the only reliable design methodology.

It is feasible however, to adopt a mechanistic approach to compare the results of a CBR design, but the criteria of assessment (e.g., vertical compressive strains in each layer, or factor of safety concepts) are poorly defined for these types of pavements and wheel loads. Using the examples given earlier, a mechanistic model of the CBR design pavement for a CAT793D had been evaluated mechanistically.

As can be seen above and from the following table, lower base and upper and lower sub-base layers have vertical strain values 10-30% in excess of the 2000 microstrain limit previously identified. Therefore, in this particular case, the resulting CBR-based design may be just about adequate for a CATIII haul road design, if the vertical compressive strain criteria can be reliably applied to all pavement layers. (Note also in this analysis, no sheeting layer has been modelled).

A similar result applies when ultra-truck wheel loads are considered (e.g., Liebherr T284, 600t GVM); in this case some 2.4m of layerworks is required above sub-grade, and the equivalent mechanistic analysis also shows strains 20% in excess of the 2000 microstrain limit in the upper- and lower sub-base layerworks.
<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
<th>$E_v$ (MPa)</th>
<th>Thickness (mm)</th>
<th>$\varepsilon_v$ (microstrain)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U Base</td>
<td>CBR &gt;80</td>
<td>350</td>
<td>243</td>
<td>221</td>
<td>6.2</td>
</tr>
<tr>
<td>L Base</td>
<td>CBR 60</td>
<td>242</td>
<td>297</td>
<td>2118</td>
<td>6</td>
</tr>
<tr>
<td>U Sub-base</td>
<td>CBR 28</td>
<td>149</td>
<td>315</td>
<td>2560</td>
<td>5.4</td>
</tr>
<tr>
<td>L Sub-base</td>
<td>CBR 16</td>
<td>104</td>
<td>1066</td>
<td>2163</td>
<td>4.1</td>
</tr>
<tr>
<td>Sub-grade</td>
<td>Clay CBR=5 (Rigid below)</td>
<td>50</td>
<td></td>
<td>1363</td>
<td>3.4</td>
</tr>
</tbody>
</table>

### T284 GVM tonne: 600

- Wheel load (tonnes): 101
- ESWL estimate (tonnes): 121
- Tyre pressure (kPa): 800

<table>
<thead>
<tr>
<th>Layer</th>
<th>CBR</th>
<th>$Z_{C_{BR}}$</th>
<th>Layer thickness</th>
<th>$Z_{ESWL}$</th>
<th>Layer thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-grade</td>
<td>5</td>
<td>1.740 m</td>
<td>Layer thickness</td>
<td>2.408 m</td>
<td></td>
</tr>
<tr>
<td>Lower Sub-base</td>
<td>16</td>
<td>0.843 m</td>
<td>0.897 m</td>
<td>1.071 m</td>
<td>1.337 m</td>
</tr>
<tr>
<td>Upper Sub-base</td>
<td>28</td>
<td>0.543 m</td>
<td>0.300 m</td>
<td>0.676 m</td>
<td>0.395 m</td>
</tr>
<tr>
<td>Lower base</td>
<td>60</td>
<td>0.242 m</td>
<td>0.302 m</td>
<td>0.304 m</td>
<td>0.372 m</td>
</tr>
<tr>
<td>Upper base</td>
<td>≥80</td>
<td>0.242 m</td>
<td>0.242 m</td>
<td>0.304 m</td>
<td>0.372 m</td>
</tr>
</tbody>
</table>

### CAT785D GVM tonne: 249

- Wheel load (tonnes): 41.7
- ESWL estimate (tonnes): 50
- Tyre pressure (kPa): 800

<table>
<thead>
<tr>
<th>Layer</th>
<th>CBR</th>
<th>$Z_{C_{BR}}$</th>
<th>Layer thickness</th>
<th>$Z_{ESWL}$</th>
<th>Layer thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-grade</td>
<td>5</td>
<td>1.202 m</td>
<td>Layer thickness</td>
<td>1.567 m</td>
<td></td>
</tr>
<tr>
<td>Lower Sub-base</td>
<td>16</td>
<td>0.583 m</td>
<td>0.620 m</td>
<td>0.702 m</td>
<td>0.865 m</td>
</tr>
<tr>
<td>Upper Sub-base</td>
<td>28</td>
<td>0.376 m</td>
<td>0.207 m</td>
<td>0.444 m</td>
<td>0.258 m</td>
</tr>
<tr>
<td>Lower base</td>
<td>60</td>
<td>0.167 m</td>
<td>0.208 m</td>
<td>0.199 m</td>
<td>0.245 m</td>
</tr>
<tr>
<td>Upper base</td>
<td>≥80</td>
<td>0.167 m</td>
<td>0.167 m</td>
<td>0.199 m</td>
<td>0.199 m</td>
</tr>
</tbody>
</table>
Similar results are also seen for a much smaller haul truck, illustrated below the equivalent mechanistic for a CAT 785D with 41.7t wheel loads.

Whilst a marginal CAT III design would appear a reasonable application for a CBR designed haul road, care should be taken if significantly weaker layerworks materials are used and each design option should be cross-checked to the mechanistic equivalent to compare the engineering response of the layers to the applied wheel loads.

What is clear, however, is the significant reduction in layerworks volumes that accompanies a mechanistic design incorporating a base layer of selected blasted rock placed directly on sub-grade, and the protection that layer affords, at comparatively small thickness, to the sub-grade, thus eliminating excessive vertical strains without recourse to excessive increases in layerworks thickness and volumes.

Using the design charts that follow as a quick estimation of layerworks requirements, for a CAT793D when incorporating a selected blasted rock layer directly above sub-grade, for comparable layerworks strength ($E_{eff}$, MPa) as previously, total pavement thickness above sub-grade reduces from 2121mm to 650mm (200mm sheeting + 450mm base selected blasted rock); and for a T284, from 2608mm to 800mm. However, as described below, the design chart approach can only be used when the application data exactly matches the assumptions used for design chart development.

**Mechanistic Design Charts for Common Haul Trucks**

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

The road design is assumed to incorporate 200mm of wearing course with a resilient modulus $E_{eff} = 350$MPa, a good-quality well-compact selected blasted rock base layer (as discussed previously), built on sub-grade/in-situ material with the indicated $E_{eff}$-modulus shown on the charts. The sub-grade material depth is limited to 3000mm, where after a stiffer layer is assumed to exist (either soft-rock or saturated material). All materials are modelled with a Poisson’s ratio of 0.35.

The charts give the base (selected blasted rock) layer thickness required for a Category I, II and III haul road, for the particular model of truck, for an in-situ/sub-grade resilient modulus of 10-300MPa (approx. CBR1 to CBR85). If any of the above parameters do not apply to the design case, then a full mechanistic model analysis is mandatory to accommodate the requirements of the application.
FUNCTIONAL DESIGN AND WEARING COURSE SELECTION

Learning Objectives

<table>
<thead>
<tr>
<th>Learning Objectives</th>
<th>Knowledge and understanding of;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The role of the wearing course in a road design;</td>
</tr>
<tr>
<td></td>
<td>Preliminary selection criteria and what constitutes an acceptable wearing course;</td>
</tr>
<tr>
<td></td>
<td>Material selection for use as a wearing course;</td>
</tr>
<tr>
<td></td>
<td>Selection criteria based on Shrinkage Product (Sp) and Grading Coefficient (Gc) measures;</td>
</tr>
<tr>
<td></td>
<td>Derivation of Sp and Gc from typical laboratory test data;</td>
</tr>
<tr>
<td></td>
<td>The role of compaction and it’s specification in wearing course method specification;</td>
</tr>
<tr>
<td></td>
<td>Dust palliatives, types, application criteria and economic assessment guidelines.</td>
</tr>
<tr>
<td></td>
<td>Application of;</td>
</tr>
<tr>
<td></td>
<td>Sp and Gc to specify a wearing course based on a mix of materials;</td>
</tr>
<tr>
<td></td>
<td>Density-moisture content curves to select and specify compaction requirements;</td>
</tr>
<tr>
<td></td>
<td>Dust palliative selection matrix to identify potential palliation solutions to mine road dustiness.</td>
</tr>
<tr>
<td></td>
<td>Calculate and predict;</td>
</tr>
<tr>
<td></td>
<td>Sp and Gc values from laboratory (road indicator) test data;</td>
</tr>
<tr>
<td></td>
<td>Road wearing course material mix ratios of two wearing course materials used to rehabilitate an existing road.</td>
</tr>
</tbody>
</table>
Introduction to Functional Design and Wearing Course Selection

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.

Wearing course material 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 (if a mechanistic type structural design is used); 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 necessarily 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 right 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 in 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 (as shown here), 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 safety and 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. ARRB and Mallard have proposed the following gradations for wearing course materials and applications. Note that Mallards data refers to applications in tropical or high rainfall environments.
Gradation alone however is not a sufficient basis for wearing course selection. By examining which wearing course material property parameters lead or contribute to the road defects listed previously, a specification has been developed for wearing course materials selection. The specifications are based on a parametric relationship suggested in Transport Recommendations for Highways (TRH) 20, but modified for mine road construction and operating parameters (which are very different from public, Federal or State ‘highways’).

The specification is based on a wearing course material shrinkage product (Sp) and grading coefficient (Gc), defined below. Note that this specification is based on AASHTO sieve sizes and if other sieve sizes are used to classify a wearing course material, corrections will have to be applied to calculate the equivalent AASHTO sieve sizes.

\[ Sp = LS \times P425 \]
\[ Gc = \frac{(P265 - P2) \times P475}{100} \]

where;
- \( LS \) = Bar linear shrinkage
- \( P425 \) = Percent wearing course sample passing 0.425mm sieve
- \( P265 \) = Percent wearing course sample passing 26.5mm sieve
- \( P2 \) = Percent wearing course sample passing 2mm sieve
- \( P475 \) = Percent wearing course sample passing 4.75mm sieve

A suitable wearing course material can be determined from the selection chart shown alongside, in terms of the two parameters that describe the material; the shrinkage product (Sp) and grading coefficient (Gc). 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 road performance problems for the mine, in addition to additional road maintenance activities.

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.

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

* Dust ratio defined as \( \frac{P_{075}}{P_{425}} \)

where \( P_{075} = \) percentage of material passing the 0,075mm sieve

\( P_{425} = \) percentage of material passing the 0,425mm sieve
If the only materials available for wearing course selection lie outside the parameter 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 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 below 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 ≥ 80%.
Similarly, in the example below, two material ‘A’ and ‘B’ and mixed in a suitable proportion to achieve a sheeting material that lies within the recommended specification. It should be noted that this approach can be used to approximate the final material mix specifications, but laboratory tests should be conducted on the mix to confirm these estimations – especially the bar linear shrinkage and Atterburg Limits estimates.

<table>
<thead>
<tr>
<th>MIX RATIO</th>
<th>39%</th>
<th>61%</th>
<th>FINAL MIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCREEN ANALYSIS</td>
<td>A</td>
<td>B</td>
<td>New Wearing Course (%) Passing (mm)</td>
</tr>
<tr>
<td>P37.5</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>P26.5</td>
<td>100</td>
<td>93</td>
<td>96</td>
</tr>
<tr>
<td>P4.75</td>
<td>97</td>
<td>55</td>
<td>71</td>
</tr>
<tr>
<td>P2</td>
<td>95</td>
<td>33</td>
<td>57</td>
</tr>
<tr>
<td>P0.425</td>
<td>82</td>
<td>29</td>
<td>50</td>
</tr>
<tr>
<td>ATTERBERG LIMITS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Limit (%) (LL)</td>
<td>21</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>Plasticity Index (PI)</td>
<td>10</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Linear Shrinkage (%) (LS)</td>
<td>5</td>
<td>0.5</td>
<td>2.3</td>
</tr>
<tr>
<td>Shrinkage Product</td>
<td>410</td>
<td>15</td>
<td>112</td>
</tr>
<tr>
<td>Grading Coefficient</td>
<td>5</td>
<td>33</td>
<td>28</td>
</tr>
<tr>
<td>CBR(%) 4-DAY SOAKED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100% Mod AASHTO</td>
<td>38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>98% Mod AASHTO</td>
<td>170</td>
<td></td>
<td></td>
</tr>
<tr>
<td>95% Mod AASHTO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90% Mod AASHTO</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.
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 achieve the specified strength by compaction.
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, (limited by the zero air void line (ZAV)). As more water is added achievable dry density reduces due to the (extra) volume occupied by pore water (less dense than soil solid particles). 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 Figure. 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 predetermined 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 (shown here by using a DCP to check new construction wearing course CBR values) 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 Figure of the compaction curve), rather than at optimum or above.

**Wearing Course Material Selection, Crushing, Blending and QAQC**

The sheeting (wearing course) material properties are based on the functional designs determined as described earlier. Prior to construction, the following testing is recommended:

- Particle Size Distribution 75mm –75um AASHTO T 27 and ASTM C 136 or local equivalent
- Maximum Modified Dry Density AASHTO T 180-61 and ASTM D1557 or local equivalent
- Atterberg Limits PL, LL, PI, and linear shrinkage AASHTO T 89 & T90 and ASTM D4943 & D4318/423 or local equivalent
- CBR 100% Mod MDD AASHTO T 193: ASTM D 1883 (4 day soak) or local equivalent.

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. 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 sheeting should proceed in two lifts of 100/150mm (according to design requirements) compacted to 95% Maximum Dry Density, as determined by Modified Compaction, to AASHTO T193 (or equivalent) with moisture content at or slightly dry of the optimum moisture content (i.e. -3% to +1% OMC ) to give a minimum CBR of 80% using between 4-8 passes of a 230kN vibratory roller.

The first pass of the roller should be on the outside edges of the layer to be compacted progressing towards the centre, overlapping the previous pass by 10%. However when rolling deep loose material all passes in a series should be overlapped by at least half a width of the roller. The gradual extension of the roller onto the unrolled surface makes it possible to apply a concentrated compactive effort on ridges and high spots and keeps the roller running at a truer surface shape.

Correct and uniform moisture content is important for compaction purposes. When too wet for compaction, the material should be harrowed and allowed to dry before attempting construction. If the layer is too thick it may be necessary to cut half the layer to the side of the road, water the lower half and remix and compact prior to cutting in the remaining half, watering and recompacting.

Field testing can be carried out using AS1289 5.8.1 nuclear densometers or AS1289 5.3.1 sand replacement (or equivalent local standard). Frequency of tests will depend on site supervision, quality and variability of material source (crusher run or borrow-pit) variations:

- for crushed and blended materials, one test per 3,600m³ placed,
- for borrow-pit sourced materials, one test every 1,800m³ placed.
The Selection and Application of Dust Palliatives

Introduction

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, as shown below.

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 than would be achieved with a drop-plate arrangement. Results can be further improved by applying dosage and pattern spray control systems which require a pump with an integrated vehicle speed delivery control to maintain approx. 0.25-0.5 litres/m² (0.25-0.5mm film thickness per m²) rates. More advanced systems, using automatic control, geo-fencing etc. helps reduce overwatering on ramps and 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 and providing records of palliation activities as may be required as part of a licence to operate.

Where watering alone is insufficient to reduce dust to acceptable and safe 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 dependent on changing material wind-erodibility or erosivity. The wearing course 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. However, when carefully chosen with regard to both the characteristics of the wearing course material itself, and the mine’s road management philosophy and operating practice, result can be excellent.

Shown below is an example of a validation test using a polymer-based treatment for mine haul roads. The evaluation analysed PM10 emissions with and without treatment and identified the re-application frequency based on an 80% dust control efficiency requirement (DCE). Results will differ from site to site, changes to traffic type and volumes, climate and sheeting material, but the general approach to assessment and cost-benefit analysis is evident. Data for this validation was collected using a mobile dust monitor to provide real-time quantitative haul road dust emissions and DCE data; quantifiable data to demonstrate compliance with industry
air quality regulations or as applied here, the system can be used to assess the effectiveness of dust suppression products by comparing dust emissions over time after watering for treated and untreated road surfaces. (Graphic courtesy RST Solutions, Real-time site emissions rate map courtesy of Proof Engineering).

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 with generally void ratios), 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 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 (≥10)</th>
<th>Sand</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>Max-in</th>
<th>Maintainable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Hygroscopic Salts</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Lignosulphonates</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
<tr>
<td>Petroleum Emulsions</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Polymer Emulsions</td>
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<td>✓</td>
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<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Tar/ Bitumen Emulsions</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</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
The broad classes of products available are described below.

<table>
<thead>
<tr>
<th>Hygroscopic Salts</th>
<th>Lignosulphonates</th>
<th>Petroleum-based products</th>
<th>Others (Sulphonated petroleum, Ionic products, Polymers and Enzymes)</th>
</tr>
</thead>
</table>

**Climatic Limitations**
- Salts loose effectiveness in continual dry periods with low relative humidity. Not suitable for low fines materials or high shrinkage product/PI low CBR<sup>2</sup> or slippery materials.
- Retains effectiveness during long dry periods with low humidity.
- Generally effective, regardless of climate but will pothole (small diameter) in wet weather where fines content of wearing course is high.
- Generally effective, regardless of climate.

**Wearing Course Material Limitations**
- Recommended for use with moderate surface fines (max 10-20%<0,075mm). Not suitable for low fines materials or high shrinkage product/PI low CBR<sup>2</sup> or slippery materials.
- Recommended for use where high (<30%<0,075mm) fines exist in a dense graded gravel with no loose material.
- Performs best with low fines content (<10%<0,075mm). Use low viscosity products on dense fine grained material, more viscous products on looser, open-textured material.
- PI<sup>3</sup> range 8-35. Fines limit 15-55% < 0,075mm. Minimum density ratio 98% MDD (Mod). Performance may be dependant on clay mineralogy (enzymes).

**Treatment Maintenance and Self-repair Capability**
- Reblade under moist conditions. CaCl<sub>2</sub> is more amenable to spray-on application. Low shrinkage product materials may shear and corrugate with high speed trucks. Shear can self-repair.
- 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.
- 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.
- Mix-in application - sensitive to construction quality. Difficult to maintain - rework. Generally no problem once cured.

**Tendency to Leach out or Accumulate**
- Leaches down or out of pavement. Repeated applications accumulate.
- Leaches in rain if not sufficiently cured. Gradually oxidize and leach out. Repeated applications accumulate.
- Does not leach. Repeated application accumulate.
- Efficacy depends on the cation exchange capacity of the host material. Repeated applications accumulate.
- Generally ineffective if material is low in fines content or where loose gravel exists on surface. Curing period required.

**Comments**
- A high fines content may become slippery when wet. Corrosion problems may result.
- Generally ineffective if wearing course contains little fine material or there is excessive loose gravel on the road.
- Long lasting – more effective in dry climates.
- Generally ineffective if material is low in fines content or where loose gravel exists on surface. Curing period required.

**Notes**

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

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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 clay, silt or fine sand 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, (as shown above) 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 below.
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 and truck-generated deterioration issues.
# 6 Haul Road Maintenance Management and Performance

## Learning Objectives

<table>
<thead>
<tr>
<th>Learning Objectives</th>
<th>Knowledge and understanding of;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Types of mine road maintenance and their associated activities;</td>
</tr>
<tr>
<td></td>
<td>Key elements of routine road maintenance activity auditing;</td>
</tr>
<tr>
<td></td>
<td>Root cause analysis in road maintenance;</td>
</tr>
<tr>
<td></td>
<td>Developing a haul road managed maintenance system;</td>
</tr>
<tr>
<td></td>
<td>Total costs analysis across a network of roads;</td>
</tr>
<tr>
<td></td>
<td>Developing vehicle operating cost and rolling resistance models in MMS;</td>
</tr>
<tr>
<td></td>
<td>Benchmarking rolling resistance and functional performance.</td>
</tr>
</tbody>
</table>

**Application of;**

- Rolling resistance assessment methodology to an operating road
- Functional performance assessments

**Calculate and predict;**

- Instantaneous rolling resistance values based on a visual haul road assessment methodology;
- Instantaneous rolling resistance values based on a defect progression model.
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 total 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 or ‘patrol’ road maintenance (blading or grading), through to resurfacing, rehabilitation and betterment, as defined below;
<table>
<thead>
<tr>
<th>Activity</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Routine (Patrol) Maintenance</strong></td>
<td></td>
</tr>
<tr>
<td>Spot regravelling</td>
<td>Fill potholes and depressions and exclude water</td>
</tr>
<tr>
<td>Drainage and verge maintenance</td>
<td>Reduce erosion and material loss, improve roadside drainage</td>
</tr>
<tr>
<td>Dragging/Retrieval</td>
<td>Redistribute surface gravel</td>
</tr>
<tr>
<td>Shallow blading</td>
<td>Fill minor depressions and ruts and reduce rolling resistance</td>
</tr>
<tr>
<td>Dust control/watering</td>
<td>Reduces loss of binder and generation of dust</td>
</tr>
<tr>
<td><strong>Resurfacing</strong></td>
<td></td>
</tr>
<tr>
<td>Full regravelling</td>
<td>Restore thickness of wearing course.</td>
</tr>
<tr>
<td>Deep blading</td>
<td>Reprofile road and reduce roughness. Remix wearing course material.</td>
</tr>
<tr>
<td><strong>Rehabilitation</strong></td>
<td></td>
</tr>
<tr>
<td>Rip, regravel, recompact</td>
<td>Improve, strengthen or salvage deficient pavement.</td>
</tr>
<tr>
<td><strong>Betterment</strong></td>
<td></td>
</tr>
<tr>
<td>Rehabilitation and geometric improvement</td>
<td>Improve geometric alignment and structural strength.</td>
</tr>
</tbody>
</table>

This Chapter is limited to discussing concepts of routine or patrol 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>

Irrespective of the maintenance management system used, there are some key elements of ‘good practice’ of mine road routine maintenance that should be observed, as listed below in an audit of routine maintenance activities.
# Routine or Patrol Haul Road Maintenance

## MINE HAUL ROAD MAINTENANCE: ROUTINE GRADING AUDIT

<table>
<thead>
<tr>
<th>DATE</th>
<th>ASSESSOR</th>
<th>ROAD</th>
<th>CREW/SHIFT</th>
<th>CHAINAGE/SEGMENT</th>
<th>ACTIVITY</th>
</tr>
</thead>
</table>

## RATING

### ROUTINE GRADING ASSESSMENT

- Moisture content/Adding adequate amounts of water
- Adequate removal of surface defects
- Existing material retrieval, no oversize/spillage mix
- Surface condition
- Road crossfall or crown (camber) minimum ±2% re-established/corrected
- Curve super-elevation re-established appropriate for curve speed and radius
- Longitudinal alignment maintained/corrected
- No windows left in carriageways or blocking roadside drains
- Table and diversion drains open

## RATING COMMENTS

<table>
<thead>
<tr>
<th>Item</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content/Adding adequate amounts of water</td>
<td>Prior to blading, water added to road / adequate natural moisture</td>
<td>Slightly dry but moist</td>
<td>No water/moisture – dry cutting</td>
</tr>
<tr>
<td>Adequate removal of surface defects</td>
<td>After blading, all defects removed and a smooth uniform surface remains</td>
<td>After blading, most defects removed and mostly a smooth uniform surface remains</td>
<td>After blading, not all defects removed and poor surface finish remains</td>
</tr>
<tr>
<td>Existing material retrieval, no oversize/spillage mix</td>
<td>Good wearing course material on shoulder/table drains was retrieved</td>
<td>Mostly tight surface, some areas of loose unbound material, some dust</td>
<td>No wearing course material was retrieved or excessive spillage/fines retrieved</td>
</tr>
<tr>
<td>Surface condition</td>
<td>Tight surface. No evidence of excessive loose/unbound material material, little dust</td>
<td>Mostly tight surface, some areas of loose unbound material, some dust</td>
<td>More than 20% loose unbound material, poor consolidation, excessively dust.</td>
</tr>
<tr>
<td>Road crossfall or crown (camber) minimum ±2% re-established/corrected</td>
<td>Road crossfall or crown correctly re-established using measuring device/visual</td>
<td>Road crossfall or crown mostly correctly applied visually</td>
<td>Poor: No or inappropriate crossfall or crown</td>
</tr>
<tr>
<td>Curve super-elevation and transitions re-established appropriate for curve speed and radius</td>
<td>Curve super-elevations correctly re-established using measuring device or visual, transitions visually acceptable</td>
<td>Curve super-elevations correctly re-established using measuring device or visual, but transitions poor</td>
<td>Poor: No or incorrect curve super-elevations &amp;/or no, transitions</td>
</tr>
<tr>
<td>Longitudinal alignment maintained/corrected</td>
<td>Longitudinal alignment correct with no undulations or grade breaks</td>
<td>Longitudinal undulations need minor correction over long distance</td>
<td>Large undulations and grade breaks over short distance</td>
</tr>
<tr>
<td>No windows left in carriageways or blocking roadside drains</td>
<td>No blocked or retrieved material left as windows in carriageway or across intersections, drains open</td>
<td>Small sections of windows left in carriageway or intersections, drains mostly open</td>
<td>Hazardous windows of material left in carriageway or intersections, drains obstructed</td>
</tr>
<tr>
<td>Table and diversion drains open</td>
<td>Table /roadside and diversion drains completed, ditches open and clear, correct flow directions</td>
<td>Table /roadside drains mostly clear and open</td>
<td>No drainage work completed /drains obstructed</td>
</tr>
</tbody>
</table>

V2.0.15
Routine or patrol grading is critical to the performance of haul roads, since the use of unpaved and unbound material will result in some inevitable deterioration under the action of traffic, as shown alongside in terms of rolling resistance increases over time and traffic. The basic purpose of grading is to maintain a satisfactory running surface, free of any extensive defects, and to keep the road well drained. Grading can have a relatively short-term effect especially with poorer types of material and reductions in rolling resistance minimal.

Improper grading usually lowers the surface and eventually, unless material is periodically bladed in from the roadside, the base layer works is eventually exposed, which would weaken the overall structure (due to moisture ingress) and could potentially damage truck tyres if a selected blasted waste rock base is used (this type of base, however, would not be susceptible to water ingress).

Good grading consists of bringing material in from the sides (winning and recovery passes) or cutting down high sections of the surface and filling the low spots with the surplus loose material. However, this should not be at the expense of loss of profile (cross-fall, crown or super-elevation, etc.). Ideally, prior to grading, water should be applied to the road surface. If the formation is damp the loose material graded into low spots may be compacted by traffic to give a more uniform surface with little loss of material. In very dry weather maintenance grading should be confined to smoothing loose material on the surface, keeping the cutting of high sections to a minimum. Major grading operations should be confined to times when the road can be left un-trafficked and the surface material damped down by the application of water.

The grading process should blade loose or wet material (after rainfall) from the outside edge to the centre of the road (common practice is to blade to the edge of the road – but this can interfere with drainage). This material when inspected and drier, should not contain excessive fines if it is intended for respooling and compaction when dried to OMC. If the loose or wet material contains excessive fines, it should be removed from the road and either screened to remove fines before being considered for resheeting, or replaced as per wearing course specifications. After heavy rain and if the wearing course is not soaked, the important task is to grade out scours in the running surface and fill in wheel ruts.

Under certain circumstances, the base material may also meet the specifications for a wearing course – most typically, where the material is crushed to a finer grading. Occasionally, the surface of the base layer can be impact rolled to produce this finer material also. If there is a sufficient thickness of sheeting, the material should be loosened across its full width and not less than 75mm deep. The sheeting material is usually well compacted and hard and not easy to rip with graders. Consequently, a number of passes with closely-spaced teeth may be required to avoid leaving hard areas between the grooves which will produce an unsatisfactory riding surface. Ideally, an offset disc harrow can also be used following ripping, to further breakdown the ripped sheeting. If the thickness of sheeting material falls below 75mm, loosening and reshaping would result in mixing of base layer and either...
Winning and recovering material passes

Blades angled as close as possible to 45deg with forward tilt to recover/win sheeting. First and second pass apply where a crowned profile is maintained. For a cross-fall across width of road, win only from the drain side. In all cases avoid blading spillage on to the road.

Cutting road surface, removing defects, shaping and mixing passes

Blade hard on surface with blade tilted back to cut.Scarify if blade not cutting to bottom of defects. Multiple passes in each direction may be required to reach the center of the road from both sides. Straddle windrows.

Spreading passes

Two or more spreading passes will be required depending on the amount of material obtained. If a crowned profile is to be maintained, the blade must not extend beyond the center of the road. When a cross-fall profile is adopted, blading can be applied in successive passes across the full width of the road.
grid rolling and/or impact rolling will be required to breakdown any oversize exposed. NB. The base layer if used in this manner to supplement the sheeting MUST meet the source specifications described earlier for wearing course materials. Where the base does NOT meet source specifications for sheeting materials, fresh sheeting material should be applied to the correct design width after loosening, then mixing, reshaping and compaction can be carried out.

Active roads should be inspected to determine extent of defects and whether a routine maintenance intervention is required – in particular, road profiles should be maintained at or near their original design profiles. Some basic road maintenance activities often carried out include:

- Scarify or top up the wearing course surface material to bring coarse fresh material to the surface - especially when the surface slicks up since surface spillage (mud, etc.) will change the characteristics of the wearing course if left on the road. Often seen as laminations (layering) of fine material.
- remove spillage and other loose material from the road surface – do not leave as windrows
- repair areas that have slumped or settled or wet spots by backfilling with base or wearing course as appropriate
- maintained drainage on road and shoulders as per specification (keep roadside drains)
- maintenance or re-establishing cross fall/crown and superelevation profiles

If the road surface is adequately designed and maintained, larger repairs will usually be required only at isolated points. Where a depression is too large to be eliminated by grading, it should be ripped, boxed out and filled with material similar to that in the adjoining road (selected blasted waste rock as per layerworks specifications) and/or wearing course (as per wearing course specifications), depending on the depth, finished to a smooth surface by grading and compacted.

If depressions or large potholes are caused by subgrade failure, the road should be repaired by excavating back (boxed out) to at least twice the depth of the base layer design thickness, the sides of the excavation being cut vertically. It will be necessary also to excavate subgrade material, replacing the full depth with selected blasted waste rock as per layerworks specifications. Sheetin (as per wearing course specifications, should be placed, finished to a smooth surface by grading and compacted.

Shallow holes may be repaired without prior treatment by being cleared of loose material, and filled with properly selected fresh wearing course. Both the road itself and the added material should be moist at the time, or should be moistened shortly after filling the hole. Patches should be finished to a smooth surface by grading and compaction.

In all cases, unless there is adequate moisture in the pavement for compaction, water should be added to achieve OMC. Compaction by vibratory rollers should follow the scarifying and reshaping processes.
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 defects shown in these Figures - a fairly large area of sinkage, squeezing 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 misreading 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.

There 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. Cracks (‘crockodile-cracks’) evident on the LHS of the road are also typically associated with too high an Sp value (too much plastic clay material in the wearing course), but, in itself, simply remedying the deficient wearing course (by increasing the aggregate content) will not address the underlying design deficiency.

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 (to OMC) 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 Sp and bring the material back to specification. This would be called ‘rehabilitation’ of the wearing course.

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 (depressions in the road in the wheel paths of the truck), 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).

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 3.5x 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.

In this case – crown looks ok – but where is the roadside drain? Water is gathering on the road under wheel positions 1, 3&4 and will eventually initiate damage to the wearing course and layerworks.
Here you can see oversize (maybe ‘base’ layer or dump rock material in the wearing course – these should be removed or broken-down (impact rolling) to prevent them from coming loose, forming potholes, traffic hazards and making the road difficult to blade.

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, as illustrated below;
typically long, flat, high traffic volume hauls 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.

That priority should also be reflected in the resources applied to design of these roads in the first instance.

In comparison, shorter (steeper) and/or lower traffic volume roads will have less of an impact on total costs across the network, since although rolling resistance may be higher than average, the penalty associated with this effect, in terms of total costs is only small. The costs associated with maintenance will not necessarily be recovered through reduced cost per ton hauled.

Mine haul road maintenance intervals are closely associated with traffic volumes, operators electing to forgo maintenance on some sections of a road network in favour of others. This implies an implicit recognition of the need to optimize limited road maintenance resources to provide the greatest overall benefit. This optimization approach is inherent in the structure of the maintenance management system (MMS) for mine haul roads. Two elements form the basis of the economic evaluation, namely:

- haul road functional performance - rolling resistance-based model of deterioration; and
- vehicle operating (VOC) 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 volumes 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 over 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 dependent 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.

Vehicle operating cost (VOC) model
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, as described in earlier Modules.

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 productivity 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**

The generic data shown below is used as an example to illustrate the use of MMS, applied to a typical surface mine haul road network comprising 5 segments of road network. 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>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>

<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 S Ramp is not maintained every day - by delaying maintenance on the S Ramp 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 dependent 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 some 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.

1 Modelling 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.

\[
RDS = RDSMIN + \left(\frac{RDSMAX - RDSMIN}{1 + \exp^{(RDSI)}}\right)
\]

Where;

\[
RDSMIN = 31.1919 - 0.05354 \times SP - 0.0152 \times CBR
\]

\[
RDSMAX = 7.6415 + 0.4214 \times KT + 0.3133 \times GC + 0.4952 \times RDSMIN
\]

\[
RDSI = 1.768 + 0.001 \times D(2.69 \times KT - 72.75 \times PI - 2.59 \times CBR - 9.35 \times GC + 1.67 \times SP)
\]

and

\[
RR = RRMN + RDS \times \exp^{(RR)}
\]
Where;

\[ RRMIN = \exp(-1.8166+0.0028V) \]
\[ RRI = -6.068 - 0.00385RDS + 0.0061V \]

<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 of wearing course</td>
</tr>
<tr>
<td>CBR</td>
<td>California Bearing Ratio of wearing course material (at 100% MDD and 4-day soaked).</td>
</tr>
</tbody>
</table>

The Figure shows a typical estimate of rolling resistance (RR determined in N/kg in previous equations, so multiply by 9.81 to give rolling resistance as a percentage- RR%) estimated using the equations above and data in the figure.

The Figure below shows the application of the model described here, to determine the typical rolling resistance values experienced across a network of roads and the reduction in average rolling resistance realised through a wearing course re-sheeting/rehabilitation project.
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 presented below. 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><strong>Extent Score</strong></td>
</tr>
<tr>
<td><strong>Extent</strong></td>
</tr>
<tr>
<td>Isolated occurrence, less than 5% of road affected.</td>
</tr>
<tr>
<td><strong>Defect degree score</strong></td>
</tr>
<tr>
<td><strong>Potholes</strong></td>
</tr>
<tr>
<td>Surface pockets marked, holes are &lt; 50mm diameter.</td>
</tr>
<tr>
<td><strong>Corrugation</strong></td>
</tr>
<tr>
<td>Slight corrugation, difficult to feel in light vehicle.</td>
</tr>
<tr>
<td><strong>Rutting</strong></td>
</tr>
<tr>
<td>Difficult to discern unaided, &lt; 20mm.</td>
</tr>
<tr>
<td><strong>Loose material</strong></td>
</tr>
<tr>
<td>Very little loose material on road, &lt;5mm depth.</td>
</tr>
<tr>
<td><strong>Stoniness - fixed in wearing course</strong></td>
</tr>
<tr>
<td>DEFECT</td>
</tr>
<tr>
<td>-----------------------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Potholes</td>
</tr>
<tr>
<td>Corrugations</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 shown here 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).

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

**TOTAL ROUGHNESS SCORE (RDS)**

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

**ESTIMATED ROLLING RESISTANCE (%)**

Refer to graph for rolling resistance percentages.
In this Figure for example, 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 \(2 \times 5 = 10\).

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 \(5 \times 2 = 10\).

In each of these Figures, it is also important to consider when the road was maintained, since if we record the number of days since last maintenance, we can then quickly build up a picture of how quickly the road has deteriorated over time. In the upper illustration, this road has not seen maintenance for several weeks, compared to the road in the lower illustration, which was only very recently maintained (bladed) and potholing has re-occurred rapidly. (Rutted and Sp of wearing course too high – hence ‘polish’ evident after blading).
Functional Performance Assessment

The approach outlined above (Qualitative rolling resistance assessments) 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>MINE HAUL ROAD FUNCTIONAL AND ROLLING RESISTANCE EVALUATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATE</td>
</tr>
<tr>
<td>ROAD</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>CHAINAGE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DEFECT</th>
<th>FUNCTIONALITY</th>
</tr>
</thead>
<tbody>
<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>
<tr>
<td>Dustiness</td>
<td>X</td>
</tr>
<tr>
<td>Stoniness - loose</td>
<td>X</td>
</tr>
<tr>
<td>Cracks - longitudinal</td>
<td>X</td>
</tr>
<tr>
<td>Cracks - slip</td>
<td>X</td>
</tr>
<tr>
<td>Cracks - croc</td>
<td>X</td>
</tr>
<tr>
<td>Skid resistance - wet</td>
<td>X</td>
</tr>
<tr>
<td>Skid resistance - dry</td>
<td>X</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NSFUNCTIONALITY DEFECT SCORE (DS) ( \sum(\text{Defect degree x defect extent}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>DS&gt;140</td>
</tr>
<tr>
<td>65&lt; DS &lt;140</td>
</tr>
<tr>
<td>DS&lt;64</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage</td>
</tr>
<tr>
<td>On road</td>
</tr>
<tr>
<td>Side of road</td>
</tr>
<tr>
<td>Erosion</td>
</tr>
<tr>
<td>Longitudinal</td>
</tr>
<tr>
<td>Cross</td>
</tr>
</tbody>
</table>
Individual mine sites will need to set their own ‘maintenance intervention thresholds (red, yellow and green rows above) at which some road maintenance activity is triggered when exceeded. In the table above, typical values are as follows:

- Road maintenance is recommended if:
  - any single critical functional defect exceeds limits (shown with #); or
  - total functional defect score (DS) ≥ *140.
- Road maintenance imminent but still trafficable when  *65 ≤ DS ≤ *139.
- Road in good condition, no immediate maintenance needs when DS ≤ *64.

...but a mine should determine these threshold values (shown above with asterix *) following its own specific operating and regulatory requirements.

The decision whether or not to maintain the road is not only based on the total DS, but also on critical (shown with 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. The values used here are specific to each mine site and its 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.
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.

<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>![Image]</td>
</tr>
<tr>
<td>Stones - loose on road</td>
<td>![Image]</td>
</tr>
<tr>
<td>Crack - longitudinal</td>
<td>![Image]</td>
</tr>
<tr>
<td>Crack - slip</td>
<td>![Image]</td>
</tr>
<tr>
<td>Crack - crocodile</td>
<td>![Image]</td>
</tr>
<tr>
<td>Skid resistance - wet</td>
<td>![Image]</td>
</tr>
<tr>
<td>Skid resistance - dry</td>
<td>![Image]</td>
</tr>
</tbody>
</table>
To aid readability and clarity of the concepts presented in this course, in-text citations have not been used, although the course draws heavily on many of the contributors to this field. The aim is to present available information in collated and readable form, rather than to present new or unproven knowledge and concepts. Inadequacies or imprecision in the referencing of this work is not a result of policy, and I do wish to acknowledge all those whose knowledge I have drawn on. To this end, you may wish to refer to the full list of texts which resourced this work and which form the basis of the design and construction guidelines summarised here. These are presented below in approximate groupings related to the content of Chapters 1-7.

General Concepts in Mine Haulage and Road Design


Safety in Mine Haulage


Geometric Design of Mine Roads

Structural Design of Mine Haul Roads
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.


Functional Design of Mine Haul Roads


Mine Haul Road Maintenance and Management


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


**Additional Electronic References**

Haul Roads Optimisation Alliance – Service providers

Haul Road Design Resources
http://haul-road-design.com/

Haul Road Design - copies of technical papers, etc.
http://mineravia.com

Road Traffic Safety Management Consulting (RTSM) (Damir Vagaja)

Road Safety Training Services (RSTS) Dave Tulloch

MINCAD Systems (CIRCLY6)

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

Haul Road Inspection Handbook (1999)

Blind Areas Study (Haul Trucks)
http://miningquiz.com/powerpoints/mobile_equipment.htm

EMESRTgate – EarthMoving Equipment Safety Roundtable - Surface

INFOMINE Technology Review – Mine Haul Roads
http://technology.infomine.com/reviews/mineroads/welcome.asp?view=full

AustRoads guides – Guide to Road Safety, Guide to Road Design. Available at
https://www.onlinepublications.austroads.com.au/?override=1

Caterpillar Global Mining Haul Road Design and Management