University of Southern Queensland

Faculty of Engineering & Surveying

# A Review on Australian Mine Haul Road Design Procedures

A Dissertation submitted by

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# ABSTRACT

The cost effective design of Mining Haul Roads is critical to the successful operation of all open cut mines within Australian and around the world. These mines rely heavily on the haul road network to transport run of mine (ROM) material. However, haul roads are often under-designed and seldom constructed and maintained to a standard that minimises total cost.

Theoretical methods of Queensland haul road design including pavement design, geometric design and functional design were researched and documented. Using design and as-constructed information obtained from mine sites an analysis was undertaken to determine how different methods of pavement designs presented different configurations. These configurations were run through CIRCLY to calculate the pavement deflection under the vehicle. The calculated deflection was then utilised in an attempt to calculate rolling resistance and the effect on fuel consumption.

However the static deflection data produced by CIRCLY was not suitable to use in determining the component of rolling resistance that can be attributed to pavement configuration. Therefore different methods of pavement design were analysed to determine their maximum deflection / deformation under similar load conditions.

Designing for minimal surface deflection would suggest that the optimal method to determine cover to subgrade is either Ahlvins Formula with Austroads Sublayering, Ahlvin's Method with Austroad Sublayering and improved subgrade, or cement modifying the base materials. All of these methods will produce an adequate design while being comparatively costs effective.

However it should be noted that none of the methods used achieved deflections near that suggested by Thompson of 3mm (Thompson 2011b) or Tannant and Regensburgs 6-8mm (Tannant & Regensburg 2001). So that irrespective of the method used the rolling resistance will be more than desired. Therefore further onsite testing is required to justify which method produces the least deflection and hence rolling resistance in a practical sense.

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## Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Anita Leigh Strack

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Signature

28/10/15

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Date

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# GLOSSARY (Sharp & Milne 2008)

**Aggregate -** A material composed of discrete mineral particles of specified size or size distribution, produced from sand, gravel, rock or metallurgical slag, using one or more of the following processes: selective extraction, screening, blasting or crushing.

**Anisotropic -** A material which has properties that vary in different directions.

**Austroads -** The association of Australian and New Zealand road transport and traffic authorities whose purpose is to contribute to the achievement of improved road transport outcomes.

**Axle -** One or more shafts, positioned in a line across a vehicle, on which one or more wheels intended to support the vehicle turn.

**Axle Loads -** That portion of the total vehicle load transmitted to the road through a single axle.

**Base -** The base is generally a layer of crushed aggregate placed on top of the subgrade or subbase. (BMA Projects Group 2012)

**Bearing Capacity -** The maximum average contact pressure between the foundation and the soil which will not produce shear failure in the soil.

**California Bearing Ratio (CBR) -** The ratio, expressed as a percentage, between a test load and an arbitrarily defined standard load. This test load is required to cause a plunger of standard dimensions to penetrate at a specified rate into a specifically prepared soil specimen.

**CDF –** Cumulative Damage Factor

**Chainage –** Longitudinal distance along a control line, typically the centre line of a road.

**CIRCLY –** CIRCular Loads LaYer Systems Software - A linear elastic layer computer program used to calculate the stresses, strains and deflections generated in a pavement in all directions under the application of a simulated load.

**Crossfall –** The slope, measured at right angles to the alignment, of the surface of any part of a carriageway.

**Deflection –** The vertical movement of a member or pavement due to the application of a load. It is an indication of the rate at which permanent deformation will occur under traffic, or due to other environmental or physical factors, over time.

**Deflection Bowl -** A representation of the shape of the elastic deformation of the pavement surface when a load is applied.

**Design Life -** The period during which the performance of a bridge or pavement is expected to remain acceptable with only routine maintenance.

**Design Vehicle -** The hypothetical road vehicle whose mass, dimensions and operating characteristics are used to establish aspects of the road geometry layout.

**Elastic Modulus (Youngs Modulus, Modulus of Elasticity) -** A measure of the stiffness of a given material. The ratio, for small strains, of the rate of change of stress with strain.

**Empirical –** A source of knowledge acquired by means of observation or experimentation.

**ESWL –** Equivalent Single Wheel Load

**Isotropic -** A material having properties that are equal in all directions.

**Pavement Deflection -** The vertical elastic (recoverable) deformation of a pavement surface due to the application of a load.

**Pavement Stiffness -** The resistance to deflection of the pavement structure.

**Resilient Modulus –** The ratio of stress to recoverable strain under repeated loading conditions.

**ROM –** Run of Mine

**Subbase -** The material laid on the subgrade below the base either for the purpose of making up additional pavement thickness required, to prevent intrusion of the subgrade into the base, or to provide a working platform.

**Subgrade -** The trimmed or prepared portion of the formation on which the pavement is constructed. Generally taken to relate to the upper line of the formation.

**Wearing Course -** That part of pavement upon which the traffic travels.

# CHAPTER 1

# 1. INTRODUCTION

## 1.1.Project Background

Prior to 1977 there was no specific guideline outlining the best way to design haul roads (Kaufman & Ault 1977). With little direction, haul roads were designed using past knowledge or experimental measures. Over time the demand on resources around the world has pushed for more efficient mining techniques. A direct result of this has been an increase in machinery size.

Kaufman & Ault's (1977a) study indicates that truck payload capacities have increased from moving as little as 20 tonne to as much 360 tonne (Gross weight of machine being 624 tonne) (Caterpillar 2014) at any one time. However, the technology used to design the haul roads that these trucks traverse has not developed at the same rate as the advancement of the machinery.

The purpose of Kaufman & Ault's study was to develop a design criteria, with recommended practices that if implemented will promote continuity and safety throughout all haulage roads.

With the above problems in mind Kaufman & Ault strived to produce a design manual coving the topics as listed below (Kaufman & Ault 1977):

- Haul road alignment
  - Horizontal alignment
  - Vertical alignment
- Haul road cross section
  - Pavement design
  - Drainage
- Road maintenance

In the following years multiple people reviewed and drew their own conclusions on Kaufman and Ault's recommendations. Two momentous manuals that have since been published and will be referred to throughout this document, is the study done by Tannant & Regensburg (2001) (Guidelines for Mine Haul Road Design) and

Thompson (2011a) (Mining Roads, Mine Haul Road Design, Construction and Maintenance Management).

Prior to Thompson producing his own manual he undertook several studies with Professor Alex T Visser at the University of Pretoria. Their first aim was to update the previous empirical method used to design pavements to a mechanistic structural design approach. From this, over the following years Thompson conducted more research and has presented a full guide on mine haul road design, construction and maintenance management. This document can be seen as an updated more recent version of Kaufman and Ault's design manual. However, Thompsons' Mine Haul Road Design manual focuses primarily on pavement design, with additional information on geometric design, maintenance and performance evaluation.

Thompson and Visser outline that there are three integral components of the total haul road design strategy, these being structural design, functional design and maintenance design (Thompson & Visser 1999) as outlined in Figure 1-1: Three Components of a Total Haul Road Design Strategy (Thompson & Visser 1999) Figure 1-1 below.

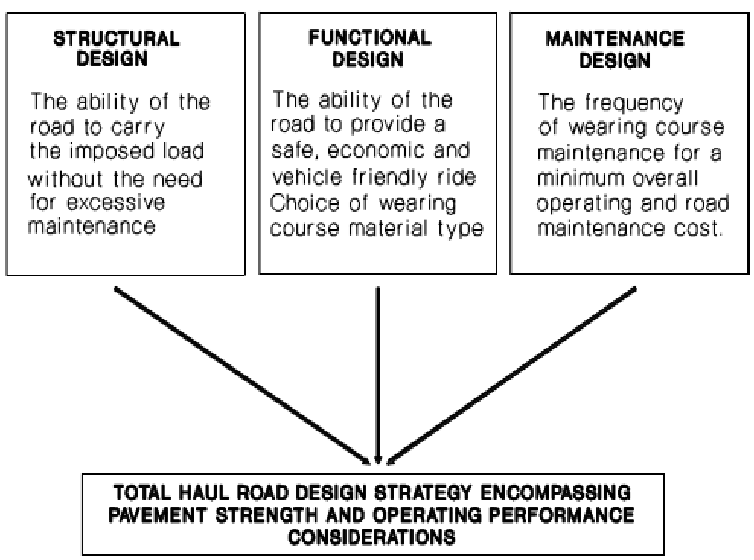



*Figure 1-1: Three Components of a Total Haul Road Design Strategy (Thompson & Visser 1999)*

More recent studies completed by Roger Thompson (2011) suggest 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 time; or
- Build a road with little design input, which needs a lot of repair, a high intensity of maintenance and rehabilitation over its life.

The first option is extremely expensive to build, but requires little ongoing maintenance, whereas the second option is cheaper to build, but requires ongoing maintenance, making it very expensive to operate.

Therefore, it is important to incorporate all aspects into the design to determine the most appropriate solution for each individual mine. If any of the components are compromised, it's usually the road performance that suffers. Increasing maintenance is simply not the answer. No amount of maintenance will fix a poorly designed road. It is essential that each stage is addressed thoroughly when undertaking detailed design (Thompson 2011b).

Over time there have been other Haul Road Design manuals written, however they are generally specific to a company or mine. For example BMA have two different manuals, one written in 1998 (BHP 1998) and an updated version written in 2012 (BMA Projects Group 2012). Their design manuals cover all aspects of road design including:

- Pavement
- Alignment design
- Intersections
- Road side furniture and signage
- Drainage
- Lighting

Rio Tinto's manual (RioTinto 2004) is similar; however, it also contains construction, maintenance and cost benefit models.

## 1.2. Project Aim

This project seeks to deliver a comparison between current practice and theoretical procedures to determine which pavement design method is most suitable to mining operations within Queensland. Overall it is anticipated that the most cost effective pavement design will consider deflection and total operating costs. The least total cost is getting the balance between capital and maintenance cost right. The less deformation that is produced by passing vehicles will result in a structural design that will require less maintenance and hence will be more cost effective to the mining operation.

## 1.3. Expected Outcomes and Benefits

This *project* is designed to investigate and present practice vs theory, and the performance prediction against actual performance on mine hauls roads in Queensland. Haul Road designs are generally undertaken on site by the mining engineering department, engineering consultants or not at all (ad hoc). It is expected that there will be very little as constructed data outlining how haul roads have been designed and constructed. It is anticipated that information will have to be gathered from photographs, survey and discussions with relevant engineering staff on site. Due to the nature of the mining industry and confidentially agreements, the mines that provide information will not be named, for the purpose of this exercise all mines will be titled Case Study A, Case Study B etc. For example the case studies aim to demonstrate firsthand the techniques used to design a haul road and the constraints that have to be met to satisfy the stakeholders. Therefore the outcome may not be the most cost effective solution however, processes have to be followed to ensure that the solution being put forward is safe as reasonably practical irrespective of the cost.

# CHAPTER 2

# 2. LITERATURE REVIEW

## 2.1. Pavement Design

Kaufman and Ault's definition of Pavement is 'A road surface that can adequately support the weight of traversing traffic without excessive deterioration of the surface caused by the traffic.' (Kaufman & Ault 1977) A typical pavement consists of a wearing course, a base, subbase and subgrade layer. All layers work together to provide a suitable road.

Various methods of haul road pavement design will be discussed and demonstrated so a comparison can be made about their performance.

### 2.1.1. Structural Design

Structural analysis is used as a method to determine the critical strains and or stresses which are induced in a pavement from traffic loading. It is normal to represent pavements as a series of layers, of different strengths / moduli. Care must be taken to ensure the method used to undertake the structural analysis is compatible with the input data. If not too many assumptions have to be made, the results may be misleading or worthless (Jameson 2012).

The strains induced within flexible pavements are mostly elastic (i.e. recoverable) however, every vertical strain is not fully recoverable. Therefore after many load repetitions permanent deformations accumulate at the subgrade level and throughout all pavement layers. These deformations may be seen in the form of rutting along the wheel path and surface roughness (Jameson 2012).

A typical stress distribution within a granular pavement is presented in Figure 2-1 below:

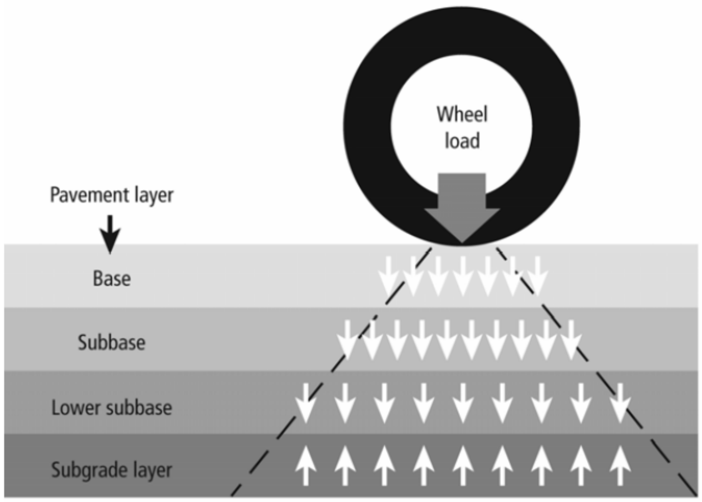



*Figure 2-1: Stress distribution within a granular pavement (Vuong et al. 2008)*

### 2.1.2. Kaufman and Ault's Method – Empirical Method

Kaufman and Ault's method of determining pavement thickness is completely empirical. Their method the 'California Bearing Ratio (CBR) Cover Curve Design' is based on the CBR penetration test. This test determines a subgrade CBR which is used to calculate the amount of material that should be placed over the subgrade to support the weight of the traversing traffic.

To conduct this test a sample of material is compacted and then subjected to an applied load. The CBR is the ratio of penetration resistance of the material compared with the standard California limestone. The only requirement of this method is the CBR of subsequent layers above the subbase be of a higher CBR than the previous layers.

To be entirely accurate the subgrade and subbase material bearing capacity should be determined by qualified geotechnical engineers. Final pavement thickness may be determined by using Kaufman and Ault's CBR Curve in Figure 2-2 (Kaufman & Ault 1977). An input of material type and vehicle wheel loads will give an output of pavement thickness. Vehicle wheel loads are determined by dividing the gross weight of the vehicle over each axle (generally not a 50-50 ratio) by the number of tyres on that axle. Kaufman and Ault recommend that if a wheel is on a tandem axle, the value calculated above should be increased by 20%. Once all wheel loads are calculated the highest wheel load of the vehicle is used to determine the pavement thickness, as illustrated in Figure 2-2 below.

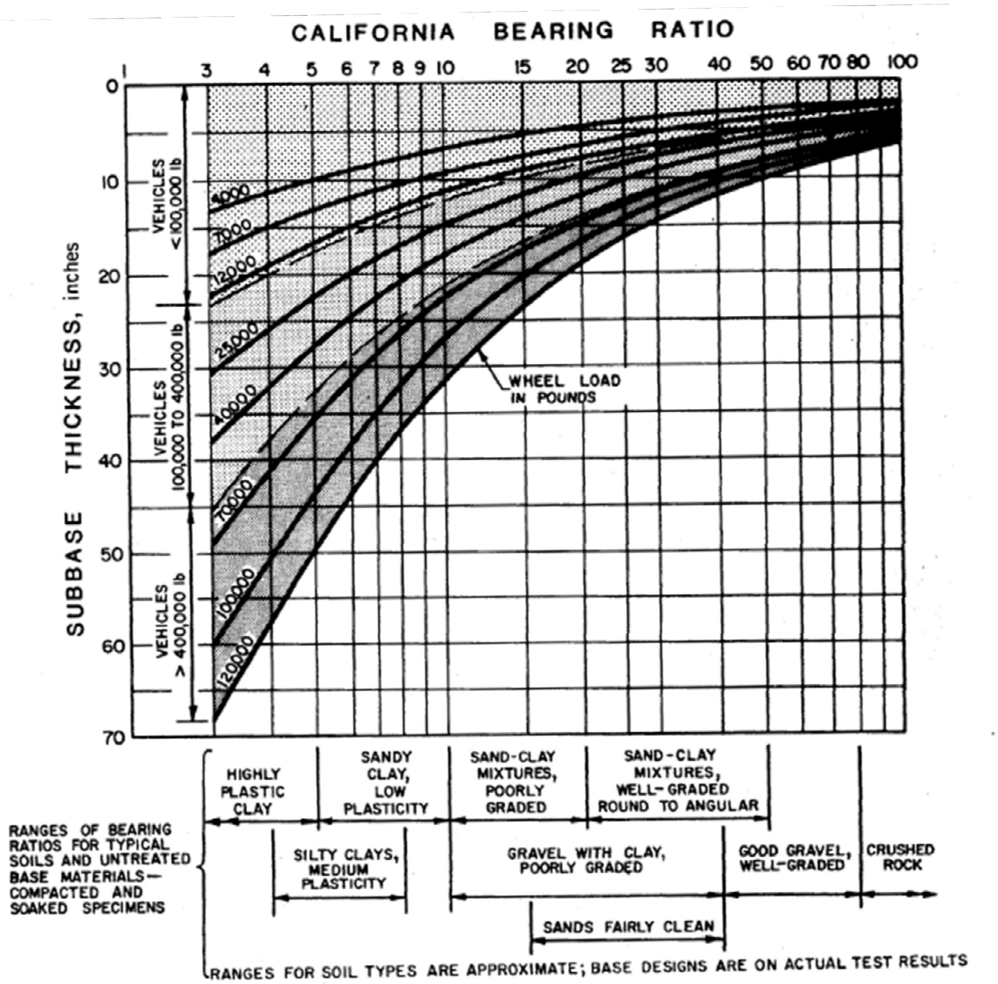



*Figure 2-2: CBR Curves (Kaufman & Ault 1977)*

For an example of how Kaufman and Ault's CBR cover design method works the following design inputs available are:

The road is to be constructed over a CBR 5 subgrade, with a maximum wheel load of 40,000 pounds (18.1 Tonne), CBR 15 material is available for the subbase and CBR 80 material available for the base.

Using Figure 2-2: CBR Curves (Kaufman & Ault 1977), the 40,000 pound wheel load curve intersects the vertical line of CBR 5 at 28 inches (710mm). Therefore the minimum depth (to finished surface level) above the subgrade must be 28 inches.

The CBR 15 material intersects the 40,000 pound curve at 14 inches (355mm), therefore the top of this material must be kept 14 inches below the road surface. And finally the CBR 80 Material intersects the 40,000 pound curve at 6 inches (150mm). Figure 2-3 shows graphically the calculated pavement design.

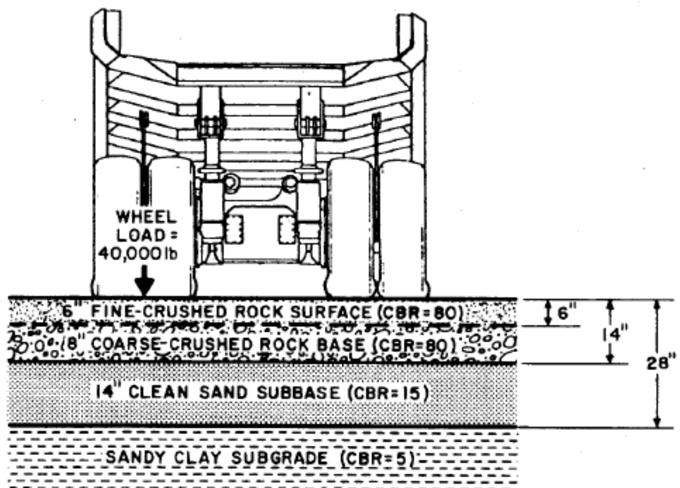



*Figure 2-3: Final Illustration of Pavement Construction (Kaufman & Ault 1977)*

Following the detailed pavement design the pavement can then be constructed. Irrespective of the materials used, Kaufman & Ault recommend that subbase construction layers should not exceed 8 inches (200mm), be compacted while moist and compacted by suitable compaction equipment (for example heavy rollers). Therefore, if the thickness of a layer exceeds 200mm, it should be staged and constructed in multiple layers. The layers shall be compacted continuously until the weight of the unit fails to compress the material (Kaufman & Ault 1977).

Alternatively Equation 2-1 (Thompson 2011a) can be used to estimate the layer thickness that would otherwise be computed from Figure 2-2.

$$z_{CBR} = \frac{9.81t_w}{P}\left[0.104 + 0.331e^{(-0.0287t_w)}\right]\left[2 \times 10^{-5\left(\frac{CBR}{P}\right)}\right]\left[\left(\frac{CBR}{P}\right)^{-\left(0.415+P\times10^{-4}\right)}\right]$$

*Equation 2-1*
*Tompson's CBR Cover Curve Formula*

Where:

$T_w$ = Truck wheel load (metric tons)
P = Tyre pressure (kPa)
CBR = California Bearing Ratio of the material (%)

This equation can be used as an estimate however it does not match Figure 2-2 exactly. Because of these slight discrepancies, for the purpose of this project Equation 2-1 will be used as a separate method.

#### 2.1.2.1. Equivalent Single Wheel Load

As seen below in Figure 2-4 at a certain point below the surface the stresses induced by the wheel loads overlap considerably. At this point the stresses are so great that the stress induced on the subgrade from the dual wheel assembly for all practical purposes, would be the same as that induced by a single wheel load. The shading of the picture is intended to suggest the distribution of critical stresses induced to the subgrade. This method was first determined for aeroplanes but it is also applicable for haul roads due to the high loadings induced. (Boyd 1949) Ultimately the Equivalent single wheel load (ESWL) allows the overall pavement depth to be decreased.

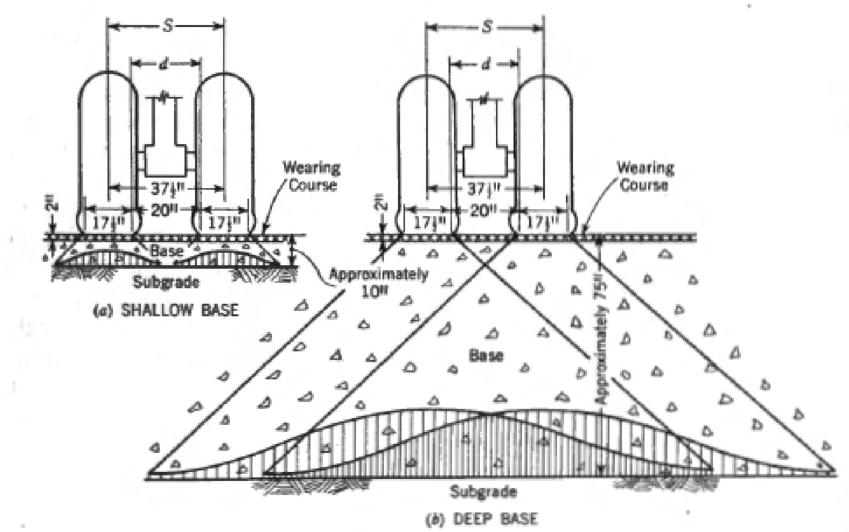



*Figure 2-4: Schematic Diagram of a B-29 Plane Wheel Assembly (Boyd 1949)*

The ESWL method was first developed by Boyd and Foster (1949) and is based on the following assumptions (Drakos 2002):

- Equalancy concept is based on equal stress
- Contact area is circular
- Influence angle is 45˚ and
- Soil medium is elastic, homogeneous and isotropic.

Tannant and Regensburg (2001) suggest that Kaufman and Aults (1977a) CBR Cover Curve Method only be used for estimating purposes not detailed design. Along with Thompson their recommended improvement is to use the ESWL instead of the single wheel load. This method assumes that the road experiences a combination of wheel loads, which increase the stress levels in lower layers resulting in a more accurate pavement design.

The ESWL should be calculated with the following conditions:

- Where the ESWL has the same circular contact area as that of the other wheel loads.
- Where the maximum deflection generated by ESWL is equal to that generated by the group of wheels it represents.

Tannent and Regensburg have adopted Foster and Ahvin's literature to present the following method for calculating the ESWL at various depths of a road cross section (Tannant & Regensburg 2001).

The deflection under a single wheel $D_s$ is calculated using Equation 2-2.

$$D_S = \frac{r_s P_s F_s}{E}$$

*Equation 2-2*
*Single Wheel Deflection*

Where:

| | | |
|---|---|---|
| $r_s$ | = | Contact radius for single tyre (m) |
| E | = | Youngs modulus of the pavement (MPa) |
| $P_s$ | = | Tyre pressure for a single wheel (MPa) |
| $F_s$ | = | Deflection factor for a single wheel |

The deflection under a group of wheels is calculated using the following:

The layer thickness $D_d$ is calculated using Equation 2-3 (Tannant & Regensburg 2001).

$$D_d = \frac{r_d P_d F_d}{E}$$

*Equation 2-3*
*Multiple Wheel Deflection*

Where:

| | | |
|---|---|---|
| $r_d$ | = | Contact radius for a group of wheels (m) |
| E | = | Youngs modulus of the pavement (MPa) |
| $P_d$ | = | Tyre pressure for a group of wheels (MPa) |
| $F_d$ | = | Deflection factor for a group of wheels |

To use either Equation 2-2 or Equation 2-3 the following assumptions are applied:

$$D_S = D_d \ \ and \ \ r_s = \ r_d$$

Tyre loads $(L_s \ and \ L_d)$ are related to the tyre pressure and contact radius. Refer Equation 2-4 (Tannant & Regensburg 2001).

$$L_s = \pi {r_s}^2 P_s \ \ and \ \ L_d = \pi {r_d}^2 P_d$$

*Equation 2-4*
*ESWL Tyre Loads*

Therefore:

$$\frac{L_s}{L_d} = \frac{F_d}{F_s}$$

*Equation 2-5*
*Tyre Load and Deflection Factor Relationship*

Equation 2-5 (Tannant & Regensburg 2001) gives a relationship between tyre load and the deflection factor. From Figure 2-5 the deflection factor can be determined for various depths and horizontal locations. These can then be substituted back into Equation 2-2, Equation 2-3 and Equation 2-5 to calculate the ESWL at various depths for the given wheel geometry.

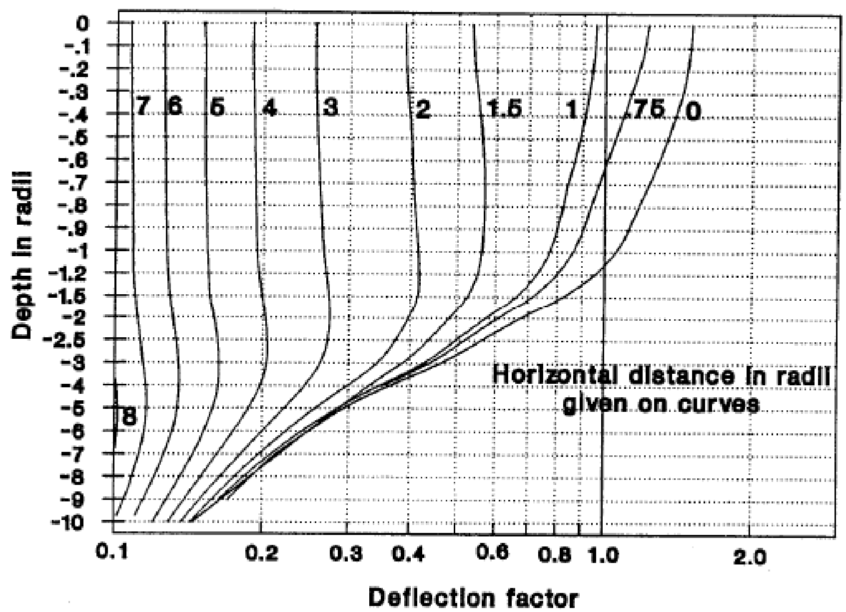



*Figure 2-5: Deflection Factor for EWSL determination with the distance normalised by radius of the tyre contact area (Tannant & Regensburg 2001).*

### 2.1.3. Ahlvin's Method – Thickness over Subgrade CBR

In 1971 on behalf of the United States Army Engineer Waterways Experiment Section, Richard G. Ahlvin a pavement engineer undertook an investigation to validate the pavement design criteria. At the time, a new jet had been developed that was significantly larger and heavier than other jets (in excess of 340 tonne), and there were concerns about whether the existing pavement could support the new jet. The purpose of Ahlvin's investigation was to establish if modifications to existing pavements were required to cater for the new jet, and to develop a new criteria for the evaluation and design of flexible and rigid aircraft pavements (Ahlvin 1971).

A special pavement was designed and constructed as an experiment to enable testing. The testing included of instrumentation measurements to determine deflection, stress and strain resulting from the static and dynamic loads, non-destructive vibratory testing to determine wave velocity and stiffness and traffic testing with multiple and single wheel assemblies.

Based on the results, the basic CBR method was modified to obtain a method for heavy loads experienced by the pavement. Due to the nature of the aircraft loads this can be related to haul roads. Overall, Ahlvins formula reflects a reduction of thickness requirements from the existing multiple wheel criteria. The cubic equation yielded the best statistical curve fit for the separation of failures and non-failures of the testing. It is suggested that Equation 2-6 be used for the computation of thickness of overlying layers required to prevent shear deformation in the supporting layers (Ahlvin 1971). Like Kaufman and Ault's method (Kaufman & Ault 1977), design inputs are subgrade CBR, tyre loads and pressure.

$$t = \sqrt{A}\left(-0.048 - 1.1562\left(log\frac{CBR}{Pe}\right) - 0.6414\left(log\frac{CBR}{Pe}\right)^2 - 0.4730\left(log\frac{CBR}{Pe}\right)^3\right)$$

*Equation 2-6*
*Ahlvin's CBR Cover Curve Formula*

Where:

| | | |
|---|---|---|
| t | = | Thickness of overlying layer (m) |
| CBR | = | Subgrade CBR |
| A | = | load / tyre pressure |
| $P_e$ | = | ESWL / A |

#### 2.1.4. Tannant & Regensburg's Method – Critical Strain / Resilient Modulus Method

In 1989, Monenco conducted a survey with the intention of discovering how Canadian mines operated with respect to Kaufman and Aults initial report. In 2001, Tannant and Regensburg set about updating the Canadian Mine Haul Road Manual (Tannant & Regensburg 2001). Tannant and Regensburg began their research by conducting a similar survey. There were six mining operations that replied to both surveys. These surveys provided Tannant and Regensburg an insight into the way Canadian mines operated and how decisions were made. Their manual covered a broad range of topics including pavement design.

Tannant and Regensburg's (2001) method of designing a pavement uses predicted stresses and strains and each layers resilient modulus. From these inputs a critical strain limit is calculated and used to establish the required moduli of each layer.

Tannant and Regensburg warn that many haul trucks are loaded above their recommended weight capacity and that this should be taken into consideration when designing a pavement.

When choosing the design CBR, choose the minimum CBR value available for an entire area and use this when calculating road pavement thicknesses. Increased fill quantities caused by overdesigning the pavement in places offers an insurance against poor road performance should the fill or subgrade become saturated.

Developments in pavement design have allowed different material properties to be taken into consideration when predicting their behaviour before construction. These properties are determined by laboratory and in-situ testing. The resilient modulus can be determined using the falling weight deflectometer (FWD) test whereas the Young's modulus of elasticity can be determined by a compression test. Repetitive loading will increase the stiffness of a material, therefore the initial Young's modulus will be less than the resilient modulus.

The strain induced in a pavement layer is a function of the applied stresses (tyre pressure, tyre size and tyre spacing) and resilient modulus of the layer. Stresses in pavement layers below the wearing course can be calculated using stress models or by using the elastic theory, assuming that a whee load creates a uniform circular load over an isotropic, homogeneous elastic half space. The assumption of homogeneity will portray some error however it is suitable for preliminary examination. Figure 2-6 illustrates a method of determining the approximate stress beneath a typical tyre, where *p* is the pressure and *w* is the equivalent diameter (Tannant & Regensburg 2001).

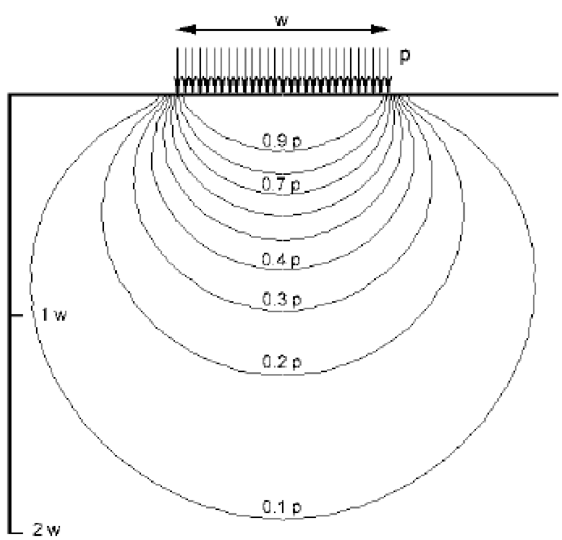



*Figure 2-6: Stress Bulbs Below a Circular Pressure Distribution. (Tannant & Regensburg 2001)*

Tannant and Regensburg recommend Knapton's method for calculating the critical strain limit for each layer. Knapton's method was developed for heavy loading conditions on docks at container ports and has been modified to suit mine haul roads. Equation 2-7 calculates the critical strain limits while taking consideration the estimated traffic over the design life (Tannant & Regensburg 2001).

$$E = 80000/N^{0.27}$$

*Equation 2-7*
*Critical Strain*

Where:

| | | |
|---|---|---|
| E | = | Allowable strain limit (Micro-Strain) |
| N | = | Number of load repetitions |

Equation 2-7 is only suitable for load repetitions between 50,000 and 5,000,000. Advice from Tannant and Regensburg is that this equation requires further calibration and should be used with caution until such time as it is updated.

Applying the theory above, a pavement can be designed in a suitable computer program using the resilient moduli. This method is based on the criteria that the vertical strain is less that the critical strain at any point. Generally, the critical vertical strain is between 1500 and 2000 micro-strain. It should be noted that the resilient modulus test is highly sensitive to the compaction and water content during compaction. Alternatively the Young's modulus gives a very conservative estimate of the resilient modulus (Tannant & Regensburg 2001).

The next step is to calculate the vertical stress distribution below the tyre. Initially the stress can be estimated based on past experience or designs with similar conditions with the stiffest material on top the next stiffest below and so on. Poisson's ratio is also required to model strain. If the strain is greater than the critical strain limit, the thickness or stiffness of the layer above that material should be increased. Alternatively if the strain is much less than the critical strain, the thickness of the layer above may be decreased. Repeat the modelling process to ensure strain is less than the critical strain at all points. Refer Figure 2-7 for a process flowchart outlining the above design process.

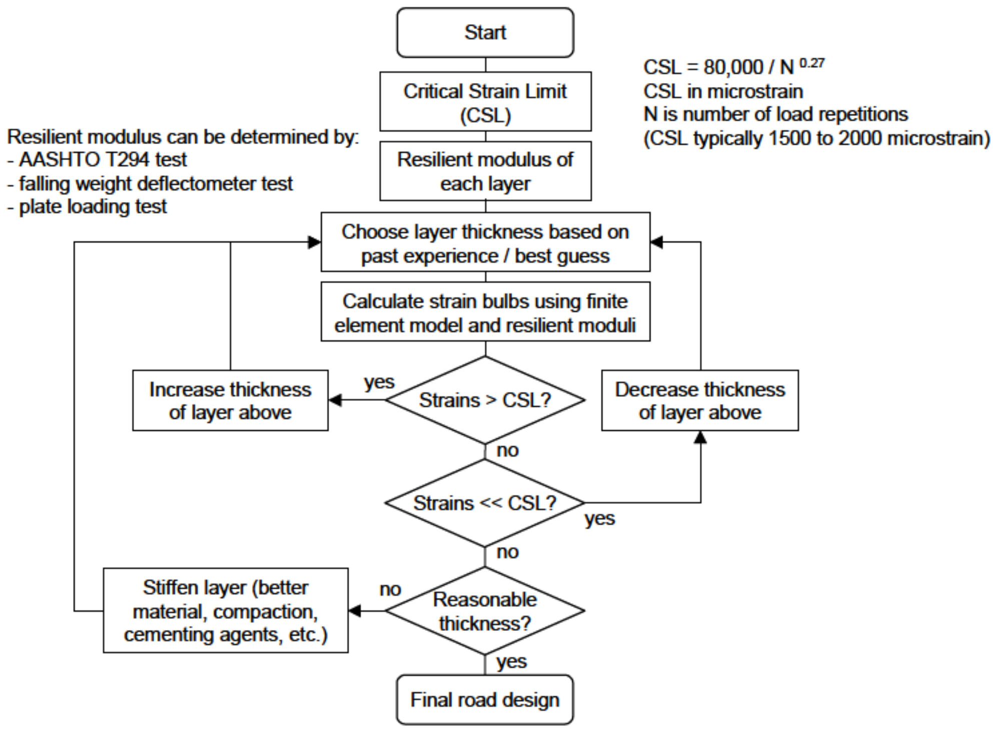



*Figure 2-7: Major Steps of the Resilient Modulus Haul Road Design Method (Tannant & Regensburg 2001)*

### 2.1.5. Thompson's Method – Mechanistic Method

Thompson suggests that a mechanistic method is more appropriate than the empirical method (Thompson 2011b). The Thompson mechanistic pavement method typically has three layers; a wearing course, a selected blast rock layer and a subgrade / in-situ or fill material layer. The intention is to limit the load-induced strains to below the critical value in the softer in-situ or fill layer.

The critical value depends on the category or road being designed, the truck size, performance requirements and road operating life. Essentially the higher the truck wheel loads, load repetitions and the operating life, the lower the critical strain will be. This value then enables the thickness of the blast rock layer to be determined so the road will perform to a satisfactory standard over the design life span.

The pavement as a whole must limit the strains in the subgrade (in-situ) to an acceptable level and the upper layers must protect the layers below (Thompson 2011b). As the vertical compressive force is transferred from the wheel point load to the pavement, the strains magnitude decreases with increasing depth. Therefore the stronger pavement materials should be used towards the top of the pavement.

Thompson recommends vertical elastic strains shall be limited to 2000 microstrains with strains greater than 2500 only being acceptable for lightly trafficked and short term roads. Another controlling design factor is the deflection deformation, this is caused by multiple passes of the heavy loads. On the wearing course this deflection should be limited to a maximum of 3mm.

To complete a design using Thompson's method, the haul road category to design must be established. This can be done using Figure 2-8. Note that the critical value of the vertical compressive strength depends on the traffic volume, and if the vertical strain exceeds 2500 microstrains there is reason to suggest that his may result in inadequate structural performance. Other input values are the effective modulus of elasticity (refer Equation 2-8), poissons ratio (v, typically 0.35) and equivalent single wheel load contact stress.

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

*Equation 2-8*
*Eff Modulus*

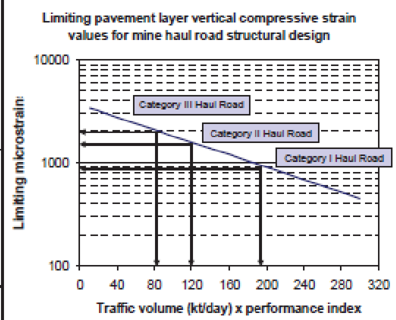
Using this information, a layered elastic model can be created in modelling software in CIRCLY[1] (or equivalent). This model will represent the various layers as discussed above.

The wearing course is modelled as a 200mm thick layer with a modulus of 350MPa. From here the blasted waste rock layer should be varied so that the maximum strain limit in any pavement layer is below the limiting strain criteria for that class of road. For calculation purposes in CIRCLY the layers should be assumed to extend infinitely in the horizontal direction, and the lowest pavement layer to an infinite depth vertically (Thompson 2011b).

Typically a modulus of 1500-3000MPa would be used for the blast rock base layer. If the compaction is poor this value may be reduced to 1500-2000MPa. This value has been derived from consideration of a cement-stabilized layer in its pre-cracked state, which corresponds closely to a well compacted waste rock layer.

[1] Alternative programs are: ELSYM5, MePADS and FLEA. Rio Tintos design manual recommends FLEA.

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




Maximum permissible vertical strains can also be determined from (*kt/day x performance index*) where performance index is defined as;

1 Adequate but fairly maintenance intensive
2 Good with normal maintenance interventions
3 Outstanding with low maintenance requirements

*Figure 2-8 Haul Road Category Descriptions (Thompson 2011b)*

Below is an example for a full laden haul truck with standard recommended tyres, inflated to 800kPa traversing all categories of road. The road design is assumed to incorporate a 200mm wearing course layer of CBR 80, a good quality, well compacted selected blast rock base layer, built on an in-situ material with an insitu modulus as shown in Figure 2-9. The assumption is the in-situ material is limited to a 3000mm layer, where after this depth a stiffer layer is assumed to exist, either soft rock or saturated material (Thompson 2011b). Any other combinations required should be individually modelled in CIRCLY. It should be noted that the wearing course is significantly weaker than the blast rock layer. The purpose of the wearing course it to provide a safe, trafficable and low cost surface for the haul road. Therefore if the pavement requires strengthening, the base and or subbase layer should be increased, simply adding to the wearing course alone will not strengthen the pavement.

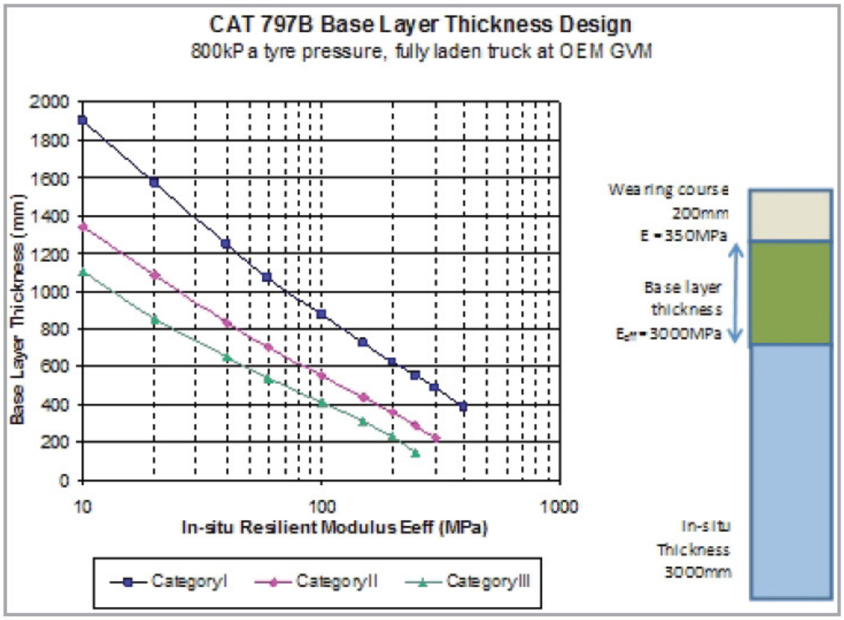



*Figure 2-9: Cat 797B Base Layer Thickness Design Example (Thompson 2011b)*

### 2.1.6. Austroads Sublayering

Austroads has produced a guide to pavement technology for Australia that assists engineers in designing pavements. While not all of this guide is applicable to haul roads, one section that can be applied is the procedure for elastic characterisation of granular materials (Jameson 2012). The modulus of the granular material is dependent on the stress level at which the material operates and the stiffness of the underlying layer. Because of this the modulus of pavement materials will decrease with depth to an extent where it is influenced by the modulus of the subgrade. As the iterative process with a finite element model that would be required to undertake this analysis is not practical, and a linear elastic layer model can be utilised. The total pavement configuration is broken up into five sublayers and each assigned a layer modulus in accordance to the following (Jameson 2012):

- For granular material placed directly onto the insitu subgrade or selected subgrade material, sublayering is required:
    - Divide the total thickness of the unbound granular material into 5 equi-thick sublayers
    - The vertical modulus of the top sublayer is the minimum of the value indicated in Table 2-1 or derived using Equation 2-9.

*Table 2-1: Suggested Vertical Modulus of Top Sublayer of Normal Standard Base Material (Jameson 2012)*

| Thickness of overlying bound material | Modulus of overlying(1) bound material (MPa) | | | | |
|---|---|---|---|---|---|
| | 1000 | 2000 | 3000 | 4000 | 5000 |
| 40 mm | 350 | 350 | 350 | 350 | 350 |
| 75 mm | 350 | 350 | 340 | 320 | 310 |
| 100 mm | 350 | 310 | 290 | 270 | 250 |
| 125 mm | 320 | 270 | 240 | 220 | 200 |
| 150 mm | 280 | 230 | 190 | 160 | 150 |
| 175 mm | 250 | 190 | 150 | 150 | 150 |
| 200 mm | 220 | 150 | 150 | 150 | 150 |
| 225 mm | 180 | 150 | 150 | 150 | 150 |
| > = 250 mm | 150 | 150 | 150 | 150 | 150 |

$$E_{v\,(top\ granular\ sublayer)} = E_{v\ underlying\ material} \times 2^{(total\ granular\ thickness/125)}$$

*Equation 2-9*
*Vertical Modulus of the Top Sublayer*

- The ratio of moduli of adjacent sublayers is derived using

$$R = \left[\frac{E_{v\ top\ granular\ sublayer}}{E_{underlying\ material}}\right]^{\frac{1}{5}}$$

*Equation 2-10*
*Ratio of Moduli of Adjacent Sublayers*

- The modulus of each sublayer may then be calculated from the modulus of the adjacent underlying sublayer, beginning with the subgrade or upper sublayer of selected subgrade material as appropriate, the modulus of which is known.
- Granular materials need to be selected such that the vertical modulus calculated for each sublayer does not exceed the maximum modulus the granular material in the sublayer can develop due to its intrinsic characteristics.
- If this criterion is not met, a material with a higher modulus needs to be used in this sublayer or an alternative pavement configuration selected.

- Other elastic parameters that may be required for granular materials for each sublayer may be calculated using Equation 2-17 and Equation 2-18.

### 2.1.7. CIRCLY

CIRCLY (**CIRC**ular Loads **L**a**Y**er Systems Software) is a computer software program created by Leigh Wardle. It was originally released as a FORTRAN program over 30 years ago and was used for analysing layered elastic media subject to surface loads. Over time the program has continuously been improved. 'CIRCLY calculates the load induced stresses, strains and displacements at any nominated point within the layered pavement system'. CIRCLY incorporate the parameters within the Austroads guidelines, and adapts and changes with each new version. There are also two additional versions of CIRCLY, APSDS (**A**irport **P**avement **S**tructural **D**esign **S**ystem) and HIPAVE (**H**eavy **I**ndustrial **PAVE**ment) for industrial facilities such as bulk shipping container terminals (Wardle 2010).

The advantage of using a mechanistic approach compared to an empirical procedure is the ability to take into account more variables and test for failure. CIRCLY also has the ability to rationally assess the likely performance of novel materials and loading conditions.

CIRCLY calculates the cumulative damage factor induced by a traffic spectrum consisting of any combination of vehicle types and load configurations (Wardle 2012). Each layer is assumed to be a horizontal plane that extends in all horizontal directions infinitely. The bottom layer may extend to a finite depth or to a semi-infinite depth. If the bottom layer is of finite depth it is assumed to rest on a rigid base with the contact either fully continuous (rough) or fully frictionless (smooth). The same properties can be applied to the interface between other layers.

#### 2.1.7.1. CIRCLY Special Features

- Material Performance (Strain Based Failure Criteria)

It has been shown that the value assigned to the subgrade modulus is possibly less critical to the outcome that the accuracy of the damage model used within the design model. If a different relationship were used, a different damage model would be derived. (Wardle 2007) Generally most performance models are represented graphically by a plot of the tolerable strain verse load repetitions. CIRCLY models are in the form of (Wardle 2012):

$$N = \left[\frac{k}{\varepsilon}\right]^{b}$$

*Equation 2-11*
*Material Performance*

Where:

| | | |
|---|---|---|
| N | = | Predicted life (Repetitions) |
| k | = | Material constant (Refer Equation 2-12) |
| b | = | Damage exponent of the material (Refer Equation 2-13) |
| ε | = | Induced strain (Dimensionless Strain) |

Due to the larger load cases of airports, ports and haul roads the subgrade may not behave linearly. For vehicles between 40-400 tonne, with vehicle movements between 10,000 to 100,000 the following formulas for subgrade material constant and material damage exponent (Equation 2-12 and Equation 2-13) should be used (Wardle 2007).

$$k = (1.64 \times 10^{-9} \times E^3) - (4.31 \times 10^{-7} \times E^2) + (2.18 \times 10^{-5} \times E) + 0.00289$$

*Equation 2-12*
*Subgrade Material Constant*

$$b = (-2.12 \times 10^{-7} \times E^3) + (8.38 \times 10^{-4} \times E^2) - (0.0274 \times E) + 9.57$$

*Equation 2-13*
*Material Damage Exponent*

$$E = subgrade\ modulus\ (MPa; Usually\ expressed\ as\ 10 \times CBR)$$

*Equation 2-14*
*Subgrade Modulus*

- Cumulative Damage Factor

CIRCLY uses the Cumulative Damage Factor (CDF) concept to present results. When the CDF reaches 1.0 the system is presumed to have reached its design life. Therefore, if the modelling produces a greater than 1.0 CDF, the pavement is predicted to 'fail'. CDF takes into account the design repetitions of each vehicle / load combination and the material performance properties used in the pavement model (Wardle 2012).

$$Cumulative\ Damage\ Factor = \sum \frac{n_i}{N_i}$$

*Equation 2-15*
*Cumulative Damage Factor*

Where:

$n_i$ = Number of repetitions

$N_i$ = Allowable repetitions

- Design Traffic and Loading

Define a 'load case' which is the anticipated vehicle movements over the design period for each vehicle or axle group (Wardle 2012).

- Wheel Loadings

The load on each wheel is defined by tyre contact radius and contact pressure (Wardle 2012).

$$a = \sqrt{\frac{P \times 9.81}{p\pi}}$$

*Equation 2-16*
*Wheel Circular Contact Area*

Where:

$a$ = Circular Contact Area

$P$ = ESWL

$p$ = Tyre Pressure (Pa)

- Global Coordinate System

The global coordinate system is used to define load locations (wheel locations), the layered system geometry and points below the surfaces where results are requires.

Take the Y-axis as the direction of travel, X-axis as perpendicular to the direction of travel and the Z-axis vertically downwards where Z=0 at the design surface. Also select if you want the results tabulated at equally spaced points along a line parallel to the x axis, or a grid of points of uniform spacing in both the X and Y Direction (Wardle 2012).

The combination of all parameters above will determine the outputs given from CIRCLY.

## 2.2. Typical Australian Regional Mines Current Pavement Design Methods

### 2.2.1. BHP Billiton Mitsubishi Alliance

Over the past two decades BHP Billiton Mitsubishi Alliance (BMA) have developed two Surface Mine Haul Road Design Manuals, one in 1998 and more recently one in 2012.

BMA defines elements of a road as described in Figure 2-10.

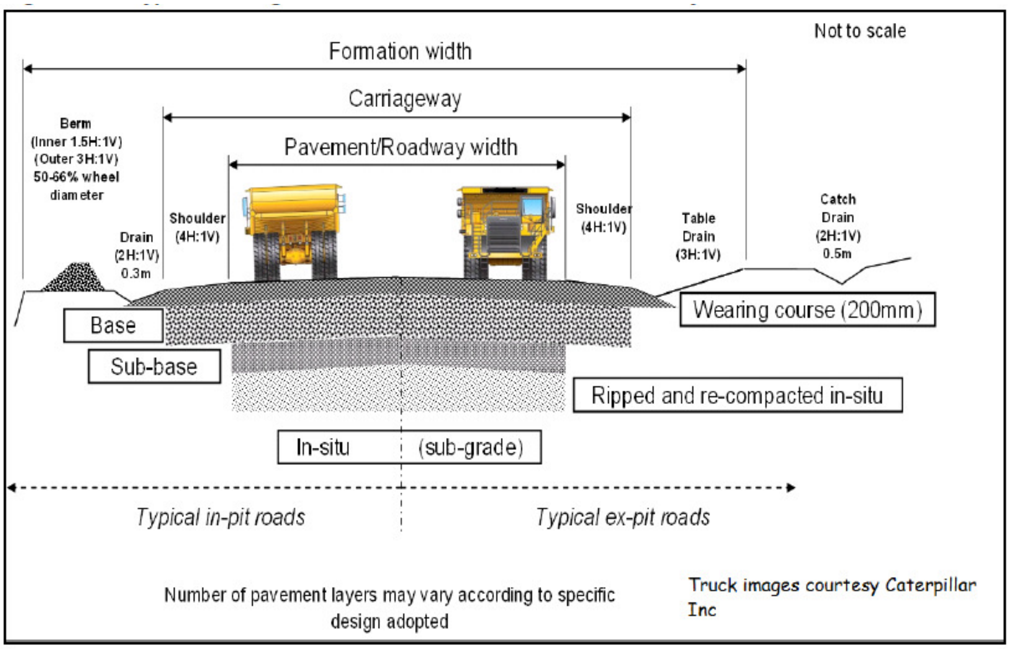



*Figure 2-10: Typical Mine Haul Road Cross Section Standard Terminology (BMA Projects Group 2012)*

#### 2.2.1.1. Pavement Design Methods

BMA allows two different design methods for their pavement designs.

##### 2.2.1.1.1. Empirical CBR Structural Design Method

This method uses Kaufman and Aults (Kaufman & Ault 1977) method as described in section 2.1.2. The cover curve method is, used to determine the required thickness of material over the subgrade (BMA Projects Group 2012), refer Figure 2-11.

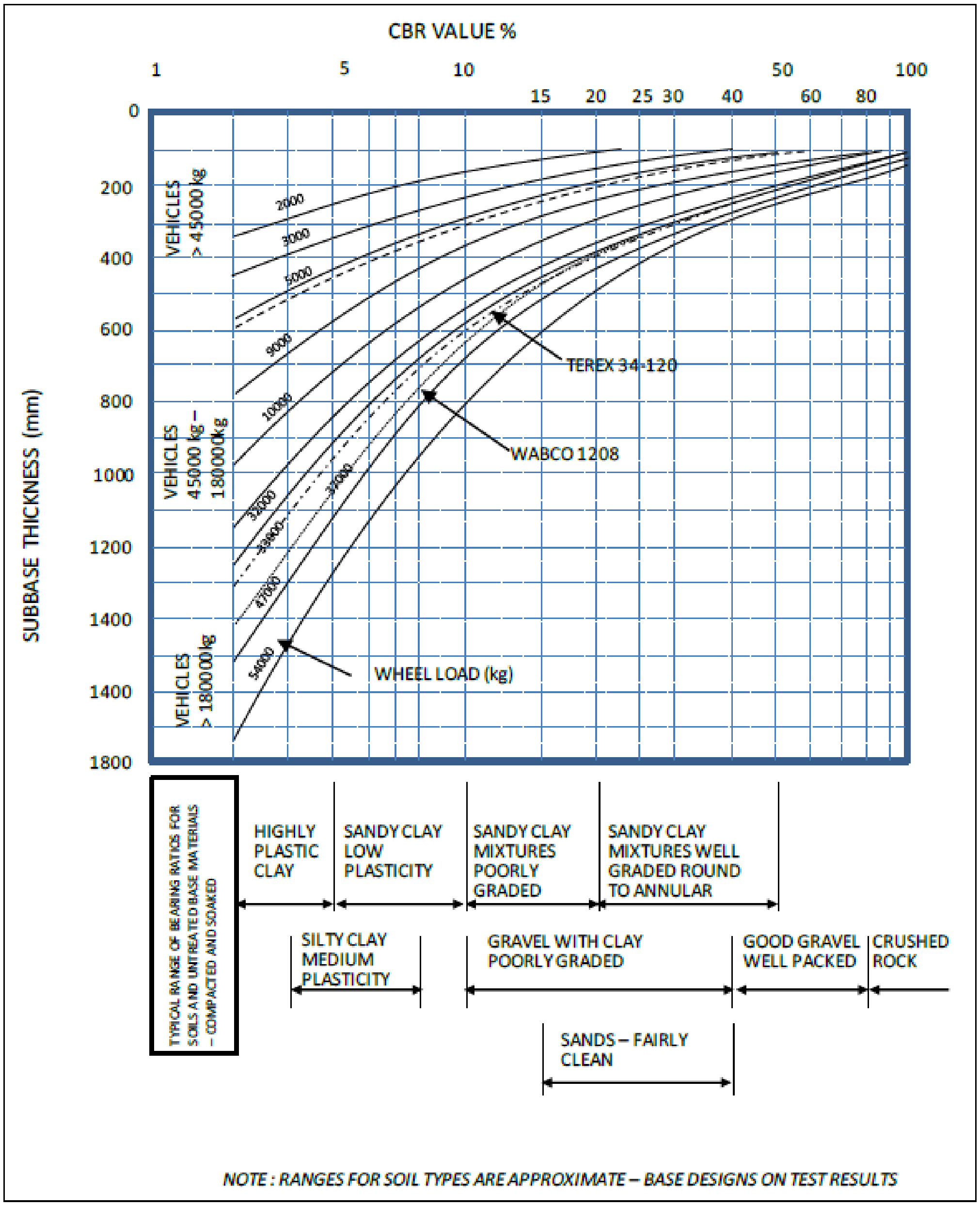



*Figure 2-11: BMA CBR Design Cover Curve (BMA Projects Group 2012)*

#### 2.2.1.1.2. Mechanistic Structural Design Method

If the mechanistic design is undertaken by an experienced pavement designer BMA accepts the method as outlined in Section 2.1.5. It allows the designer to analyse a broad range of pavement types, loading conditions and pavement materials using first principles. This form of analysis removes the need for extrapolation of historic design charts. Because haul roads have non-standard loads and loading conditions and generally non-standard pavement materials (locally sourced material) this method is more appropriate (BMA Projects Group 2012). BMA do not specify which method of pavement design is preferred.

### 2.2.2. Rio Tinto

Rio Tinto also allows two different design methods for their pavement designs.

#### 2.2.2.1. Empirical CBR Structural Design Method

This method uses Kaufman and Aults (1977a) method as described in section 2.1.2. It is a conservative approach which requires no understanding of the stresses, strains and deflections that occur within a pavement.

#### 2.2.2.2. Mechanistic Structural Design Method

Rio Tinto suggests the mechanistic approach is more efficient and subsequently cheaper than the CBR method. However it requires a thorough understanding of the design inputs. Rio Tinto permits the use of CIRCLY and FLEA (Finite Layer Elastic Analysis) programs to undertake the pavement structural design. The importance of accurate absolute values of Young's modulus and Poisson's Ratio are stressed and that without these an accurate pavement design cannot be undertaken (RioTinto 2004).

Benefits of the Mechanistic approach for Rio Tinto regardless of whether stress or strain criteria are used are (RioTinto 2004):

- Rational cost/benefit decisions can be made in regard to alternative construction materials, compactive efforts and layer thicknesses. With modern software it is a simple matter to evaluate alternative pavements which are theoretically equivalent,
- Designs can be extended to new and heavier trucks on a rational basis, and
- Back analyses can be made of actual pavements, which have performed well or badly, to provide mine-specific design criteria.

Two different approaches within the mechanistic design can be undertaken. One is to limit the subgrade and subbase strains to a certain value (either vertical strains or lateral (tensile) strains), the other is to limit subgrade vertical stresses to a set criteria. The main disadvantage of strain based designs is that they are dependent on having accurate values for the absolute values of resilient moduli. If a stress based design is used, the designer only has to have a reasonably good idea of the relative stiffness of the different pavement layers, and the absolute values do not matter.

Refer Equation 2-11 for a strain based failure criteria. It can be rearranged to give strain at which failure occurs with N repetitions (RioTinto 2004).

## 2.3.Pavement Design Materials

### 2.3.1. Granular Materials

Unbound granular pavement (typically crushed rock, gravel, soil aggregate and granular stabilised materials) have no significant tensile strength and develop shear strength through particle interlock. They tend to deform through shear, densification and disintegration (Jameson 2012).

A granular subbase must provide (Vuong et al. 2008):

- Sufficient stiffness to distribute traffic loads transmitted through the pavement base, reducing their intensity to a level which will not cause excessive permanent deformation of the subgrade.
- Provide a working platform on which base materials can be transported, placed and compacted to the required standards.
- Depending on the pavement design requirements, drain the base and / or protect the subgrade from moisture infiltration.

The requirements of a good granular pavement material is presented in Table 2-1:

*Table 2-2: Pavement Material Requirements (Vuong et al. 2008)*

| Property | Definition | Range | |
|---|---|---|---|
| workability | the ability to be placed, compacted and formed to the required condition and shape | construction | |
| economy | the material must be available and workable at an acceptable cost | | |
| strength/stiffness | the ability to resist loads without unacceptable deformation or induce tensile fatigue in surfacings | | in-service |
| hardness | the ability to withstand load without fracture and particle breakdown | | in-service |
| durability | the ability to maintain its characteristics with time | | in-service |
| volume stability | the ability to resist significant changes in volume as conditions, such as moisture content, change | | in-service |
| wear resistance | the ability to resist erosion, abrasion and polishing | surface* course | in-service |
| surface finish | the ability to accept and maintain a bituminous surfacing | surface* course | in-service |
| impermeability | the ability to resist moisture penetration and resultant loss of load bearing capacity and stiffness | surface* course | in-service |

There are some other cases where impermeability is needed, e.g. basecourse layers.

The behaviour of the materials in service is governed by many factors which are related to the following (Vuong et al. 2008):

- The intrinsic properties of coarse particles, including hardness, surface friction and contamination, and the geological origin and history of the source rock from which the material is derived
- Manufactured aggregate properties such as particle shape, size and surface texture, particle size distribution, fractured faces, nature and quantity of fine particles, and fillers – these factors are related to processes used during manufacture to produce the final product
- Compacted layer properties such as density, moisture content and particle orientation, which are in turn related to the construction and compaction processes
- Boundary conditions such as in-situ moisture and temperature regimes, and the stresses applied at the boundaries of the constructed pavement – these are external influences that will influence both short and long term behaviour.

### 2.3.2. Wearing Course

The road surface is slightly different to the other pavement layers. Not only should it provide a comfortable (smooth) wearing course it should also take into consideration dust control, traction and rolling resistance.

Typically surface selection is based on local knowledge and past experience. A good running surface will prevent increased vehicle and maintenance costs and assist the vehicle to safely traverse the designed route. The following material types are considered suitable for haul road surface construction (Tannant & Regensburg 2001):

- Compacted gravel
- Crushed stone
- Ashphaltic concrete
- Roller compacted concrete
- Stabilised earth

A summary of the material advantages and disadvantages is presented in Table 2-3.

*Table 2-3: Advantages and Disadvantages of Various Road Surface Materials (Tannant & Regensburg 2001)*

| Material | Advantages | Disadvantages |
|---|---|---|
| Compacted gravel & Crushed rock | Relatively smooth, stable surface<br>Relatively low construction cost<br>Low deformation under load<br>Ease of construction<br>Low rolling resistance | Frequent maintenance required<br>Source material may require screening/crushing<br>Dust problems in dry weather<br>Erodible if flooded<br>Potential frost action (fines > 10%) |
| Asphaltic concrete | High coefficient of adhesion<br>Minimal dust problems<br>Smooth, stable surface<br>Low rolling resistance<br>Low maintenance cost<br>High vehicle performance speeds<br>Low deformation under load | Ices easily in cold weather<br>Needs base layer with CBR = 80+<br>High construction cost<br>Specialized construction<br>Impractical for tracked vehicles |
| Rollcrete | High coefficient of adhesion<br>Very low rolling resistance<br>Minimal dust problems<br>Smooth, stable surface<br>Very low maintenance costs<br>High vehicle speeds<br>Very low deformation under load | High construction costs<br>Impractical for tracked vehicles |
| Stabilized earth | Can decrease sub-base thickness<br>Stabilize weak sub-grade | Not suitable as surface layer |

Rutted surfaces and soft pavements force the tyre, hence the vehicle to always travel uphill (Tannant & Regensburg 2001).

No matter which material is chosen as the wearing surface it should have the ability to (Thompson & Visser 2000):

- Provide a safe and vehicle friendly ride without the need for excessive maintenance
- Be adequately trafficable under wet and dry conditions
- Shed water without excessive erosion
- Resist the abrasive action of traffic
- Sufficiently sealed to reduce excessive dust in dry weather
- Sufficiently rough to reduce tyre slippage in wet weather
- Low cost and easy to maintain

### 2.3.3. Anisotropic Pavement Materials

Austroads suggests that an unbound granular material should be classed as anisotropic, ie the modulus in the vertical direction is different from that in the horizontal direction. Vertical modulus ($E_v$) can be calculated using the sub-layering procedure as described in part 2.1.6. The vertical modulus is taken to be twice the horizontal modulus. This assumption has been used because pavement materials are generally compacted in horizontal layers and exhibit a preferred particle orientation. Historically using an anisotropic material has provided a better fit between calculated and measured deflections (Jameson 2012). Equation 2-17, Equation 2-18 and Equation 2-19 suggest the relationships required to model anisotropic materials.

$$E_H = 0.5E_v$$

*Equation 2-17*
*Horizontal Modulus*

$$F = \frac{E_v}{(1 + V_v)}$$

*Equation 2-18*
*Shear Modulus*

$$v = v_h \ (Commonly\ 0.35)$$

*Equation 2-19*
*Poisson's Ratio*

However other literature suggests that there has been very little testing undertaken to suggest that anisotropy should be used for granular materials. Results from different investigations have indicated that it is difficult to establish a relationship for the change in anisotropic properties in different materials (Karasahin & Dawson 2000).

In naturally occurring soil deposits, grains are sedimented under a gravitational force which results in non-spherical grains situated with their long sides perpendicular to the direction of the gravitational force. This naturally occurring phenomenon, results in greater stiffness in the vertical direction than the horizontal direction. If an isotropic material is subject to stress that is not isotropic i.e. not the same in all directions, the material will not strain isotopically. Once a granular material has been compacted to achieve maximum density to provide adequate support and reduced deflection the layer will almost become anisotropic due to the vertical load applied (Karasahin & Dawson 2000).

### 2.3.1. Isotropic Pavement Materials

Isotropic materials have the same modulus in both horizontal and vertical directions. Thompson method of mechanistic design assumes that pavement material behaviour is perfectly linearly elastic, homogenous and isotropic (Thompson 1996). CIRCLY 6.0 haul road section is based on Thompsons design method and also utilises isotropic material (Wardle 2015).

Therefore for the purposes of this *project,* pavement materials will be modelled with isotropic properties whereas the subgrade will be considered to exhibit anisotropic behaviour.

### 2.3.2. Determination of Modulus

Without laboratory testing it can be difficult to relate resilient modulus to different soil parameters for unbound materials (Mokwa 2009). As the moduli of unbound granular materials are stress dependent and also dependent on moisture and compaction levels there is very little published data available (Jameson 2012). Wherever possible it is important to undertake testing of the soil conditions to determine the resilient modulus. If this is not possible an approximation has to be made. Many different correlations have been made between CBR and resilient modulus (Mokwa 2009). After testing undertaken by Department Transport and Main Roads (DTMR) Queensland, they decided that 10 x CBR was not the most appropriate determination of modulus for a range of CBR. Instead they adopted two different formulas, one for granular materials with a CBR less than 15 and another for CBR greater than 15. Refer Equation 2-20 and Equation 2-21 (Carteret & Jameson 2009):

$$E = 21.2 \times CBR^{0.64}$$

*Equation 2-20*
*Resilient Modulus for Granular Materials (CBR < 15)*

$$E = 19 \times CBR^{0.68}$$

*Equation 2-21*
*Resilient Modulus for Granular Materials (CBR > 15)*

Note: the vertical modulus for the subgrade material is minimum:

$$E = 10 \times CBR$$

*Equation 2-22*
*Subgrade Resilient Modulus*

This method produces pavement material modulus of 350MPa which is considered the maximum for a CBR 80 material compacted to 95% standard maximum dry density, which matches Austroads approximation.

Table 2-4 discusses the differences between resilient module for granular materials adopted by DTMR and Austroads. It also lists the adopted resilient modulus that will be used for this *project*.

*Table 2-4: Resilient Modulus for Granular Materials*

| CBR (Soaked) Minimum (DTMR 2015) | Subtype (DTMR 2015) | Maximum Vertical Design Modulus (MPa) (DTMR 2009) | Vertical Design Modulus (MPa) (Jameson 2012) | Adopted Resilient Modulus for this *Project* |
|---|---|---|---|---|
| 80 | 2.1 | 350 | 350 | 350 |
| 60 | 2.2 | 300 | 300 | 290 |
| 45 | 2.3 | 250 | 250 | 240 |
| 35 | 2.4 | 200 | | 205 |
| 15 | 2.5 | 150 | | 120 |

### 2.3.3. Microtexture / Macrotexture

Microtexure is the texture of aggregate particles on the pavement surface and is a primary characteristic that affects skid resistance. Mictotexture wavelengths are typically less than 0.5mm. Should the wavelengths be within the range of 0.5-50mm they are considered macrotexture. Macrotexture is primarily controlled by the aggregate gradation of the surface and directly affects noise and skid resistance in wet weather. Refer Figure 2-12 for schematic. (Jackson et al. 2011)

The wavelengths induce deformation onto tyres and suspension as well as vibrations. Shock absorbers and tyres are designed to improve passenger comfort while reducing the energy lost due to the vibrations. Surface texture influences rolling resistance and fuel consumption by inducing these vibrations. (Jackson et al. 2011)

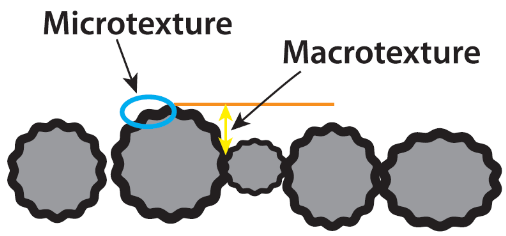



*Figure 2-12: Schematic of the Effect of Aggregate on Different Scales of Texture. (Jackson et al. 2011)*

It has been suggested that a smoother road will decrease the vibrations on the tyre and suspension hence decrease fuel consumption. However, this will vary depending on the scale of roughness, vehicle speed and vehicle type. (Jackson et al. 2011)

### 2.3.4. Rolling Resistance

Rolling resistance is one of the only accurate methods of linking pavement condition to vehicle operating costs. Rolling resistance is a function of the type of wearing course material used, the traffic speed and volume of the road (Thompson 2005). Listed below are different definitions of rolling resistance in relation to haul roads:

- Rolling resistance is the amount of drawbar pull or tractive effort required to overcome the retarding effect between the haul truck tyres and the ground (Tannant & Regensburg 2001).

- Rolling resistance is a measure of extra resistance to motion that a haul truck experiences and is influenced by tyre flexing, internal friction, wheel load and road conditions (Thompson 2011b).

- Rolling resistance is the power required to pull a tyre up and out of a rut, which is constantly being recreated by the tyre. Rolling resistance is generally expressed in terms of percent road grade or in terms of resistance force as a percentage of the GVW (Tannant & Regensburg 2001).

- Rolling Resistance is defined as the mechanical energy converted into heat by a tyre moving for a unit distance of roadway (Willis et al. 2015).
- Vehicle rolling resistance is the force required to keep a tyre moving. If the tyres are moving at a constant speed, the rolling resistance force will balance with the traction force between the road and tyre (Jackson et al. 2011).
- Rolling resistance is the force resisting the motion when a body (such as a ball, tyre, or wheel) rolls on a surface. It is mainly caused by non-elastic effects; that is, not all the energy needed for deformation (or movement) of the wheel, roadbed, etc. is recovered when the pressure is removed (Mukherjee 2014).

Rolling resistance is neither equivalent nor proportional to the friction between the tyre and road it is primarily due to the losses from the deformation induced on the tyre by the pavement. The losses are due to the fluctuating stresses and strains induced in the tyre as the tread comes in and out of contact with the pavement (Jackson et al. 2011).

Figure 2-13 shows that increased rolling resistance will decrease the truck speed and increase the fuel consumption.

Overall if rolling resistance of the tyres can be reduced, and fuel consumption improved, it is a cost effective option without negatively affecting the overall performance of the vehicle.

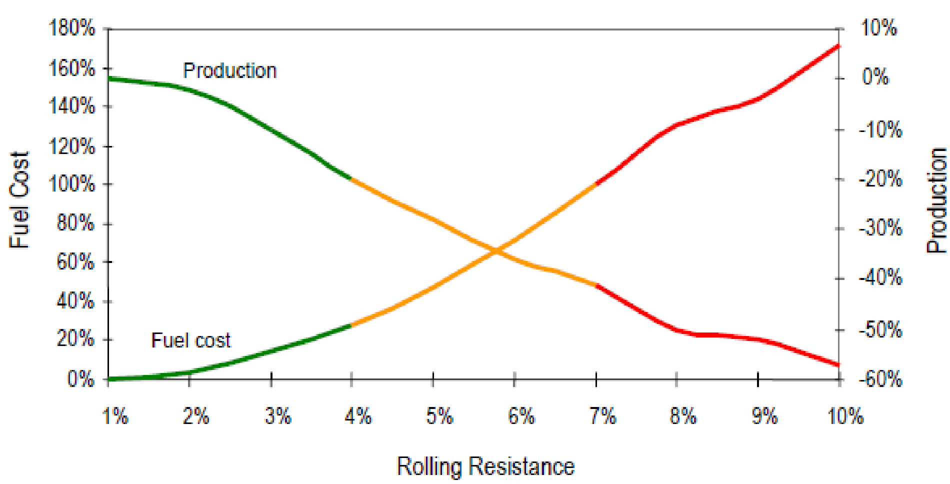



*Figure 2-13: Rolling Resistance (Performance Vs Rolling Resistance) (Holman 2006)*

### 2.3.5. Calculating Rolling Resistance

Rolling resistance consists of multiple components:

- Internal power train friction / frictional forces
- Tyre flexing under load / tyre inflation pressures
- Tyre penetration / road deflection
- Aerodynamic forces (air resistance)
- Gravity when driving on slopes (grade resistance)
- Transmission losses
- Air temperature
- Vehicle speed

(Willis et al. 2015) (Tannant & Regensburg 2001)

In order to calculate the rolling resistance data must be obtained for a moving vehicle. Firstly the power dissipation should be calculated using the mechanical response of the pavement and then converted into a rolling resistance force. For the purpose of this project the link used to associate rolling resistance to the structure induced pavement was deflection / deformation under the vehicle.

Within the last five years different method have been documented to calculate rolling resistance from deflection. However none of the literature is applicable to heavy mining vehicles.

Chumpin's method was developed for bituminous pavement, his assumptions were that the pavement was considered a multilayered structure whose layers have either linear elastic or viscoelastic behaviour. The vehicle's tyres are non-dissipative and a quasi-static regime assumed. The vehicle is moving at a constant speed and the pavement viewed as a semi-infinite medium, homogenous in the driving direction (Chupin et al. 2010).

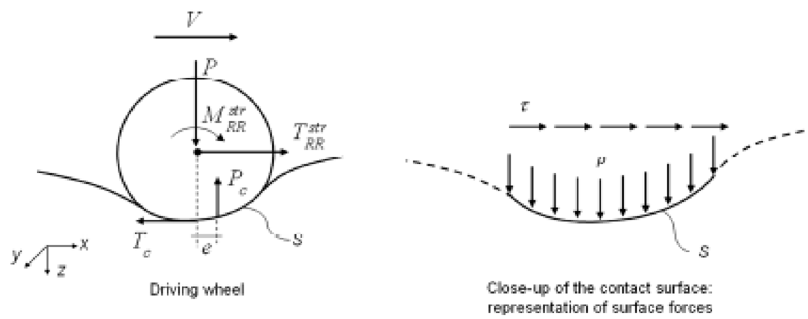



*Figure 2-14: Diagram of resulting forces applied to the wheel (Chupin et al. 2010)*

Chumpin's paper is designed to undertake a theoretical calculation, however the data obtained from CIRCLY is for a static truck i.e. has no velocity component. Therefore Chumpin's method was not suitable for use. In order to use this method of analysis the stress / strain data available cannot be symmetrical on both sides of the wheel.

Jamieson and Cenek undertook some practical testing on the rolling resistance induced by pavement deflection. However the largest vehicle used in their study was an Isuzu FTR (road registerable 15 tonne truck). A linear regression was developed to demonstrate the rolling resistance force calculated from deflection on-road measurements. It was found that the pavement deflection was the most significant predictor in relation to rolling resistance. Their conclusion was that there was a 4:1 ratio between rolling resistance and fuel consumption when driving at a steady speed (Jamieson & Cenek 2004). Due to the size difference between an Isuzu FTR and Cat 793 rolling resistance data cannot be extrapolated and therefore this method is not applicable.

Thompson and Visser developed a roughness defect score as a way of gauging the performance of a haul road. This score is developed by undertaking an onsite evaluation of the wearing course functionality. A rating is given to the defect (e.g. pothole, corrugation, rutting etc.) on how much of the road is affected (the 'extent') and how bad the particular defect (the 'degree') is on a scale of 1-5. The 'extent' is then multiplied by the 'degree' to give a defect score. If the roughness defect score exceeds the maximum allowed on the acceptability chart, maintenance is generally required. Refer Appendix B for an example of a Functional and Rolling Resistance Evaluation sheet (Thompson & Visser 2006).

Thompson has also produced a graph showing how rolling resistance affects the roughness defect score. Actual road tests were undertaken at 20, 30 and 40km/h to demonstrate how rolling resistance increase with increased road defect score (Thompson 2005). The results are presented in Figure 2-15.

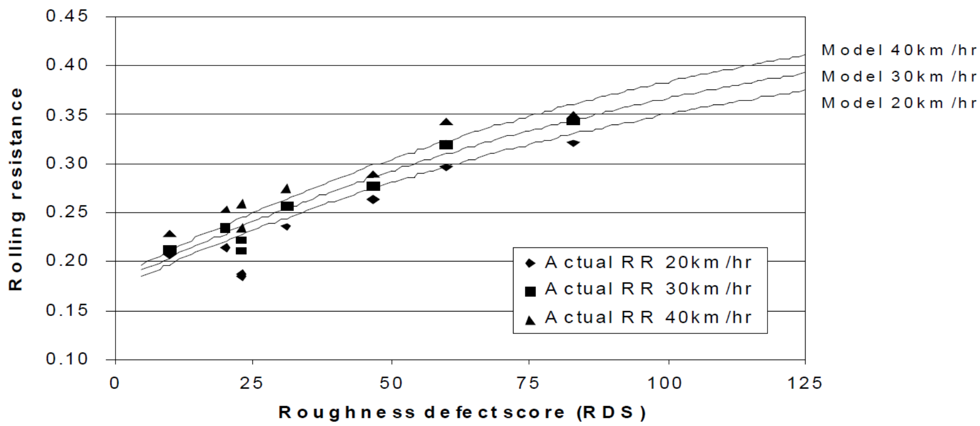
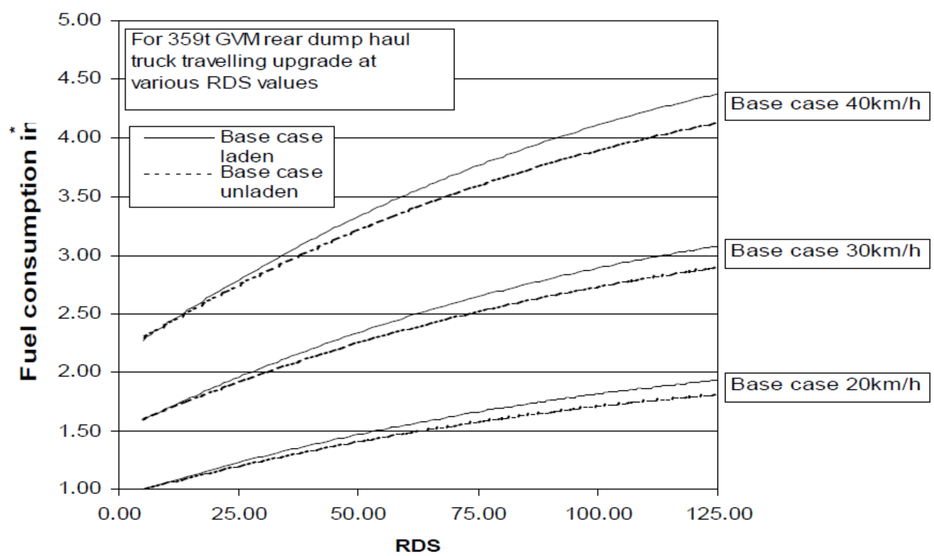



*Figure 2-15: Correlation Between Actual Test Data and Rolling Resistance RDS Model (Thompson 2005)*

This can be directly related to fuel consumption. Figure 2-16 represents the increase in fuel consumption from a base case RDS of 5 on a 0% grade (Thompson 2005).




| | Speed (km/h) | 20 | 30 | 40 |
|---|---|---|---|---|
| Fuel consumption index increment per 1% increase in grade | Laden | 0.49 | 0.74 | 0.99 |
| | Unladen | 0.43 | 0.65 | 0.86 |

*Figure 2-16: Mine Haul Truck Generic Fuel Consumption Model Showing Effect of RDS on Fuel Consumption Index (Thompson 2005)*

Finally one other approac that could be applied to provide an indication of deflection and rolling resistance is a table produced by Cat Global Mining (Caterpillar 2015) presented in Figure 2-17.

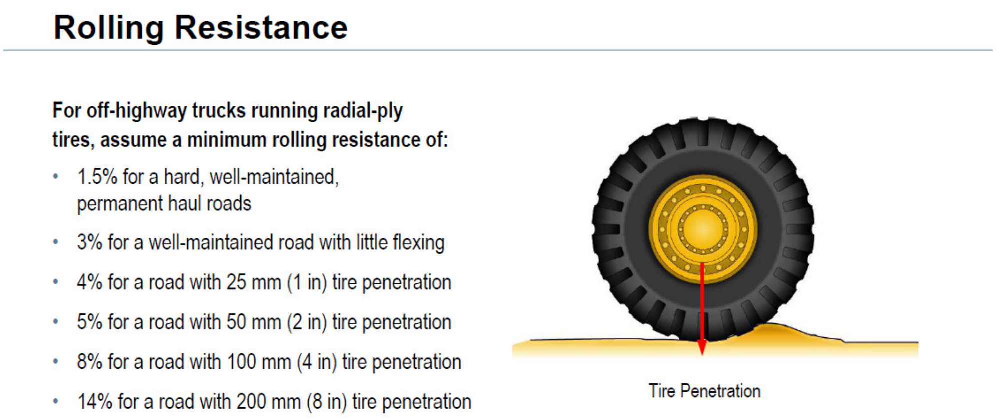



*Figure 2-17: Caterpillar Rolling Resistance Estimation (Holman 2006)*

### 2.3.1. Deflection

Ultimately it is the pavement structure design that will carry the weight of the passing vehicles over the design life of the road without excessive maintenance. Poor quality roads are often caused by deformation of one or more of the road layers being too weak or saturated. Thompson suggests that deformation at the top layer of pavement must be reduced to no more than 3mm (Thompson 2011b). Whereas Tannant and Regensburg (2001) recommend a 6-8mm deflection is adequate. Due to rolling resistance being difficult to calculate, deflection will be used as a measure of pavement competence.

## 2.4. Vehicle Operating Costs

There are many costs that are added together that result in vehicle operating costs. These can be seen in Figure 2-18. Some of these costs will be discussed within section 2.4

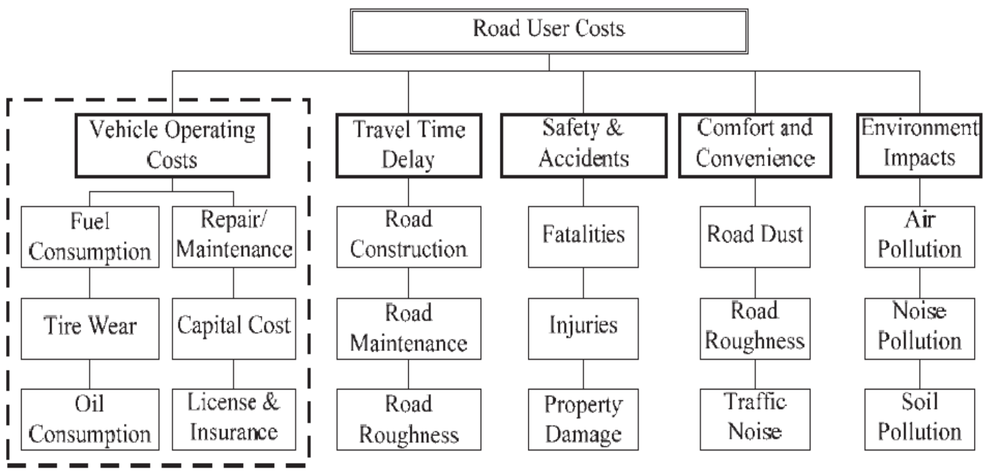



*Figure 2-18:Components of Road User Costs (Chatti & Zaabar 2012)*

The running costs of heavy duty mining equipment are strongly influenced by fuel consumption as displayed in Figure 2-19. Even the smallest improvement in fuel economy has a large impact on overall running cost. This also has a follow on effect that the total pollution omitted can be reduced (Roche & Mammetti 2015).

### 2.4.1. Fuel Consumption

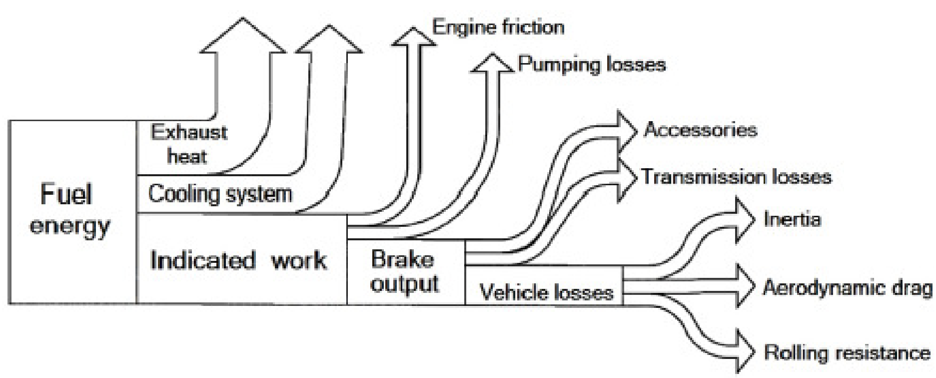



*Figure 2-19: Fuel Energy Split (Roche & Mammetti 2015)*

The Caterpillar performance handbook volume 40 produced an hourly fuel consumption table (Caterpillar 2010a). After volume 40 this table was no longer included. This data is still considered current and the most accurate available.

Caterpillar's typical descriptions for low, medium and high applications are as follows:

**Low:** Continuous operation at an average gross weight less than recommended. Excellent haul roads. No overloading, low load factor.

**Medium:** Continuous operation at an average gross weight approaching recommended. Minimal overloading, good haul roads, moderate load factor.

**High:** Continuous operation at or above maximum recommended gross weight. Overloaded, poor haul roads, high load factor.

Average engine load based on application description above:

**Low:** 20% - 30%

**Medium:** 30% - 40%

**High:** 40% - 50%

By designing a haul road to minimise the rolling resistance the fuel consumption application may change from high to medium. For example this may result in an approximately a 20% decrease in the hourly fuel consumption.

Table 2-5 presents the hourly fuel consumptions for different off highway trucks.

*Table 2-5: Off Highway Trucks Hourly Fuel Consumption (Caterpillar 2010a)*

| Off Highway Trucks Hourly Fuel Consumption | | | |
|---|---|---|---|
| **Model** | **Low (litre)** | **Medium (litre)** | **High (litre)** |
| 770 | 20.4-30.6 | 30.6-40.8 | 40.8-51.0 |
| 772 | 23.6-35.3 | 35.3-47.1 | 47.1-58.9 |
| 773F | 28.3-42.5 | 42.5-56.6 | 56.6-70.8 |
| 775F | 28.7-43.1 | 43.1-57.4 | 57.4-71.8 |
| 777D | 37.5-56.3 | 56.3-75.0 | 75.0-93.8 |
| 777F | 37.1-55.7 | 55.7-74.2 | 74.2-92.8 |
| 785C | 53.7-80.6 | 80.6-107.5 | 107.5-134.4 |
| 785D | 54.5-81.4 | 81.4-108.6 | 108.6-135.9 |
| 789C | 70.6-105.9 | 105.9-141.2 | 141.2-176.5 |
| 793D | 90.8-136.2 | 136.2-181.6 | 181.6-227.0 |
| 793F | 96.5-144.8 | 144.8-193.1 | 193.1-241.3 |
| 797F | 147.9-221.8 | 147.9-295.7 | 295.7-369.6 |

### 2.4.2. Tyre Wear

For applications suitable to haul roads there are two different types of tyres. These lead to two vastly different performances. Bias-ply tyres (Figure 2-20) have a bulky casing composed of many criss-crossed nylon layers. These tyres tend to flex causing deformation of the casing and hour glassing of the section of tread in contact with the ground. This results in uneven contact pressure and ‘scissoring’ of adjoining ply layers, increasing the case stress and heat build-up (Woodman & Cutler 1997).

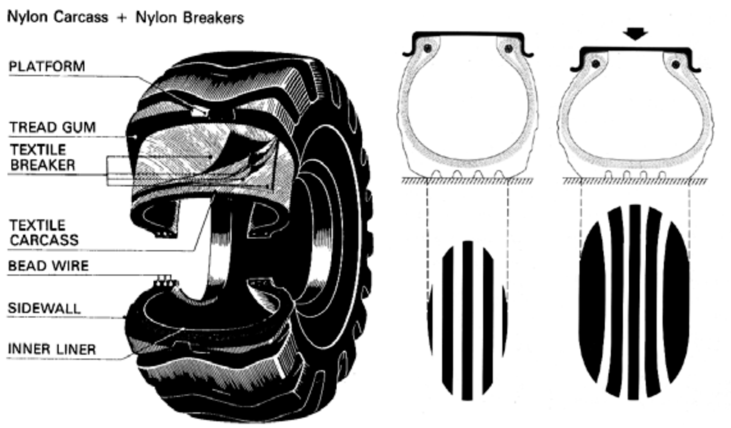



*Figure 2-20: Bias-Ply Tyre Construction and Tread Pattern (Woodman & Cutler 1997)*

Radial tyres (Figure 2-21) have a thin casing constructed of a single radially orientated steel ply layer which is contained by several circumferentially aligned steel tread belts. The advantage of a radial tyre over a bias-ply tyre is there is minimal deformation as the flexing is absorbed by the radial casing. The steel belts act like a tank track providing uniform ground pressure. Due to the minimal deformation the radial tyres produce less heat and stress therefore is more suited to high speed applications (Woodman & Cutler 1997).

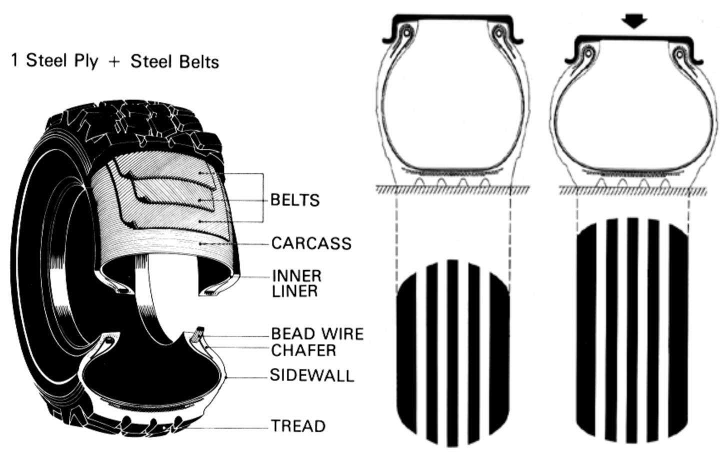



*Figure 2-21:Radial Tyre Construction and Tread Pattern (Woodman & Cutler 1997)*

The advantage of radial tyres over bias-ply tyres is they have lower fuel consumptions as their deformation / penetration is less due to minimal side wall flexing and they have lower rolling resistance and friction (Woodman & Cutler 1997). Tyre penetration depends on the weight carried, number of tyres in contact with the ground and condition of the road surface. Depending on the wheel load, when the soil is weaker the more tyre penetration or rutting will occur. Tyres penetrating the surface are not the only way for rolling resistance to increase, if the pavement flexes under the load the effects are nearly the same. In both cases the tyre is effectively running 'uphill' (Tannant & Regensburg 2001).

### 2.4.3. Tyre Pressure

Tyre manufactures do not recommend tyres being inflated beyond 700kPa. For the purposes of this project 700kPa will be used with the exemption of Thompsons Blast Rock method (Thompson 2011b) whose charts assume an inflation pressure of 800kPa. Over inflation will decrease the contact area on the surface. Over inflation will also increase the likelihood of uneven wear, cuts and impact damage (Woodman & Cutler 1997). If a tyre is inflated to its correct pressure the benefits will include, maximum traction and braking, optimum cornering ability, optimum enveloping flexibility to minimise the effects of road irregularities and reduced downtime (Holman 2006).

## 2.5. Geometric Design

Geometric design includes horizontal and vertical alignment design, stopping distance, sight distances, road width and superelevation. Overall the purpose of geometric road design is to design a carriageway that is safe to traverse for all road users. Approximately 50% of all transport accidents analysed during Thompsons investigations in 2009 could be directly contributed to road design and operation. Of these, 60% were related to non-standard acts (human error) and the remaining 40% relating to sub-standard geometric design, with maintenance and pavement design having very little influence (Thompson 2009).

Human factors are the most difficult to eliminate when designing a haul road. It is recommended that to prevent an accident the road should be more accommodating to human error. Therefore the more that is known about human error the more designers can try to accommodate for their actions (Thompson 2009).

Recommendations from Kaufman & Ault, Thompson, Tannant & Regensburg have been summarised below.

### 2.5.1. Vertical Alignment

#### *2.5.1.1.* Stopping and Sight Distance

Definition of Sight Distance: The extent of peripheral area visible to the vehicle operator. This must be sufficient to enable a vehicle travelling at a given speed to stop before reaching the hazard. (Kaufman & Ault 1977) Manufacturer specifications should be consulted to determine the distance required to bring a truck to a stop. Vehicle stopping distances must be calculated for all vehicles that will traverse the road being designed. Ultimately the distance from the driver's eye to the obstruction must always be equal to or greater than the distance required to safely stop the vehicle (Tannant & Regensburg 2001).

It should be noted that that most formulas used to calculate the stopping distance do not take into consideration excessive heat build-up that may consequently cause break fade or brake failure. (Kaufman & Ault 1977) Consult manufacture specifications to determine the distance required to bring the design vehicle to a stop.

Care should always be taken so that adequate sight distance is available on both vertical and horizontal curves. On a vertical curve the road surface limits the sight distance whereas berms, cuttings, trees and structures limit the horizontal distance (Kaufman & Ault 1977). When 150m cannot be achieved for a horizontal sight distance on a curve or bend, a layback (LB) is used to keep any obstructions away from the line of sight (Thompson 2011b).

#### 2.5.1.2. Truck Operator Blind Spots

An example of a mining haul truck operator's vision of the ground is shown below in Figure 2-22. Operators do not have full 360 degrees vision. Trucks are often left hand drive and the operator's visibility envelope will vary from machine to machine. However, when evaluating sight distance, and critically, intersection sight distances, it is important to consider whether or not the combination of the truck positioning on the road and the road geometry itself, will facilitate the required sight distance. (Thompson 2013)

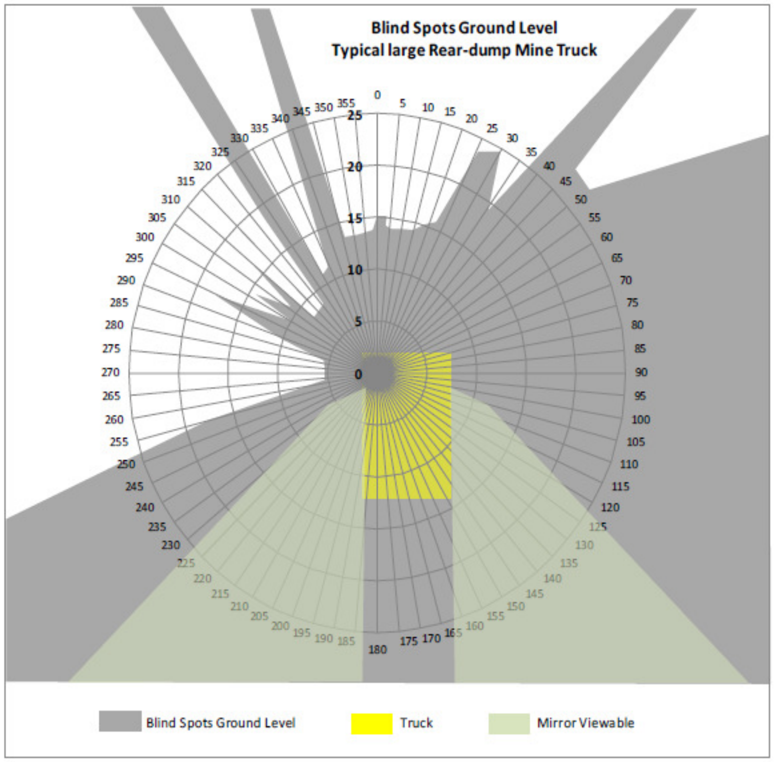



*Figure 2-22: Blind Spots at Ground Level – Typical Large Rear-Dump Mine Truck (Thompson 2013)*

#### *2.5.1.3.* Incline, decline and ramp gradients

Ideally grades should be continuous not a combination of grades or grade breaks. Both of these combinations create long travel times, so ideally the optimal grade is somewhere in between a long flat ramp (where resistance is low) and a short steep ramp (where resistance is high) (Thompson 2011b).

Grades are complicated and should take into consideration production economics. Road grade is directly related to rolling resistance. Performance charts provided by machine manufacturers show the impact of grade on performance. If an uphill grade is reduced, haulage cycle times can be increased and fuel consumption and stress on the machine can be minimised.

Kaufman and Ault describe multiple advantages and disadvantages to grade.

- Production benefits neglect construction economics
- Typically flatter grades cost more to construct
- Individual mines and companies have their own rules and regulations that prohibit flexibility

- Mine geographic locations limit vertical and horizontal design
- Individual mines may be willing to sacrifice haulage cycle times and fuel consumption for the reduction of capital cost.
  (Kaufman & Ault 1977)

Therefore it is the responsibility of the designer to take into consideration as many factors as possible when designing a road to develop the optimum solution for each location. Past experience indicates that the optimum maximum grades lie somewhere between 8-11% (Thompson 2013).

#### *2.5.1.4.* Vertical Curves

A vertical curve provides a smooth transition from one grade to another, their length should be adequate to drive comfortably and provide enough sight distance at the design speed (Kaufman & Ault 1977). Where possible vertical curves should always be greater than the minimum value calculated. Should the sight distance be reduced below the stopping distance, speed limits should be applied or sight distances increased.

### 2.5.2. Horizontal Alignment

Horizontal alignment or longitudinal alignment has many factors, including: - width of road, horizontal curves, superelevation and, cross-fall sight distances. All of these attributes similarly affects the haulage cycle time and production cost.

#### *2.5.2.1.* Width of road

It is imperative that the road width is wide enough to ensure safe vehicle manoeuvrability on both straight and curved sections of road. Each mine has different sized vehicles therefore road widths will vary depending on the vehicle not a generic standard. Should a road be too narrow, tyre life may be drastically reduced as the operator may run into safety berms when passing another vehicle or traversing a corner. Continual contact between a tyre and the safety berm may cause sidewall damage, uneven wear and cuts (Tannant & Regensburg 2001).

Use the widest vehicle on a site to determine the proposed road width. Table 2-6 displays the factor which should be multiplied by the width of the largest truck to determine a road width. Safety shoulders are incorporated in the carriage way width, whereas drainage features should be included in the formation width (Thompson 2011b).

*Table 2-6: Width of Road (Thompson 2011b)*

| Number of Lanes | Factor multiplied by width of largest truck on road |
|---|---|
| 1 | 2 |
| 2 | 3.5 |
| 3 | 5 |
| 4 | 6 |
| For switchbacks and other sharp curves and/ or a road with high traffic volumes or limited visibility, a safe road width should be designed with an additional 0.5 x vehicle width | |

Alternative factors should be considered prior to finalising a road width. Local widening may be required to accommodate equipment larger than the primary road users, such as shovels and draglines. If on a single lane road, the sight distance is less than the stopping distance, additional clearance should be provided for moving vehicles to avoid a collision with the stalled or slow moving vehicle (Tannant & Regensburg 2001).

If mining operations elect to increase the largest vehicle size in a mining fleet, assessments should be made in relation to road width. The roads may not be wide enough to accommodate for an increased truck width and may require widening.

#### *2.5.2.2.* Horizontal curves

Ideally horizontal curves should be designed to have the maximum radius possible (ideally >200m). This will keep the haul road smooth and consistent (Thompson 2011b). Minimum design radius and sweep paths should then be checked using a vehicle auto turn program. The sweep paths will show the overall extents of a vehicle when undertaking a turning manoeuvre and if additional road width or curve widening is required.

If the radius has to be smaller than the minimum recommended radius, speed limits must be applied. Constant grades will allow for constant operator speeds, which in turn will provide consistent haulage times and increase truck performance.

Increasing a grade through a horizontal curve will slow a truck on both haul and return trips. If possible place horizontal curves where the grade is flatter. Using a larger radius where possible will assist with haul cycle times and help reduce the wear and tear on both the road and machine (Tannant & Regensburg 2001).

#### *2.5.2.3.* Super-elevation

Ideally super-elevation should allow the outward centrifugal force experienced by the truck to be balanced by the lateral (side) friction between tyres and the road (Thompson 2011b). When traversing a curve high lateral tyre forces are generated. Over time these forces contribute to high tyre wear and ply separation. Superelevation helps to eliminate the above forces (Tannant & Regensburg 2001).

If a road was superelevated to the full extent (equal to the vehicle weight component) steering would be effortless however there is a practical limit (Max 10%) since high cross slopes around a corner can cause slow moving vehicles to slide down the cross slope. Another impact is that the higher loads will be induced on the inside wheels again increasing tyre and machine wear and tear (Tannant & Regensburg 2001).

Table 2-7 below shows the typical super-elevation rates based on the speed a vehicle is traveling and the radius of the curve (Thompson 2011b).

*Table 2-7: Super-elevation Rates* (Thompson 2011b)

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

Typically super-elevation development lengths are a percentage of the curve radius and allow the driver to gradually manoeuvre the vehicle through the curve.

- Run out lengths are 25-34% of the curve radius and
- Run in lengths 66-75% if the curve radius.

These are shown graphically below in Figure 2-23.

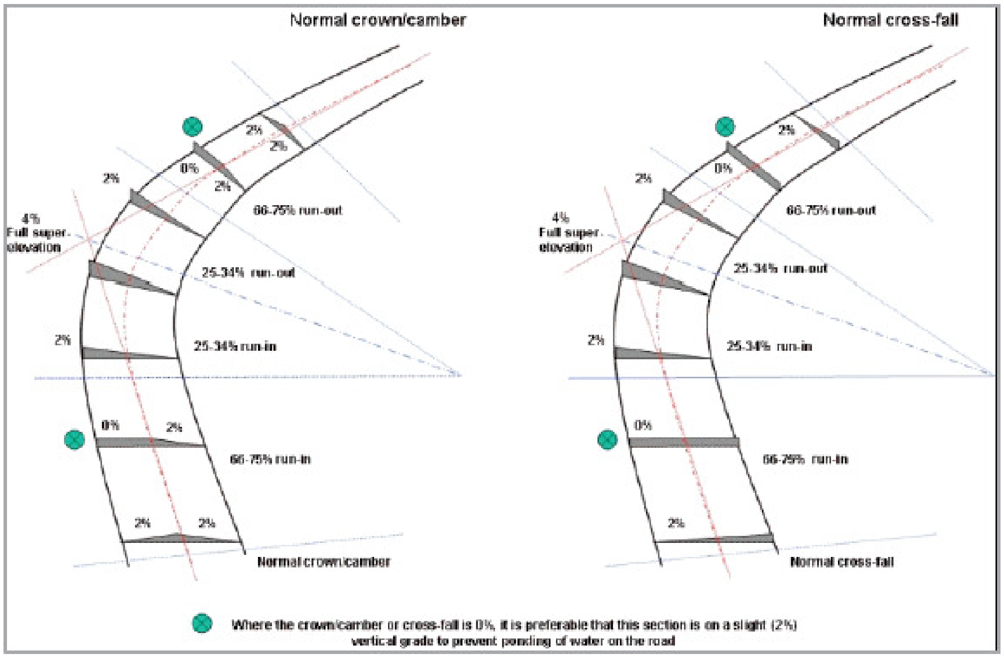



*Figure 2-23: Typical Super-elevation Development Lengths (Thompson 2011b)*

Figure 2-24 illustrates the importance of geometric design and positioning of the vehicle in relation to tyre wear. This directly relates back to rolling resistance and fuel efficiency. This also shows the importance of routine road maintenance and a smooth wearing course. Tyres can be significantly overloaded when a vehicle falls into a table drain or mounts a bund. Situations like these increase the likelihood of cuts, rock penetration, and internal damage to the tyre. Even when the vehicle is correctly loaded, overloading can occur due to road geometry. It is important that pavement geometric and structural design decrease the likelihood as much as practically possible (Woodman & Cutler 1997).

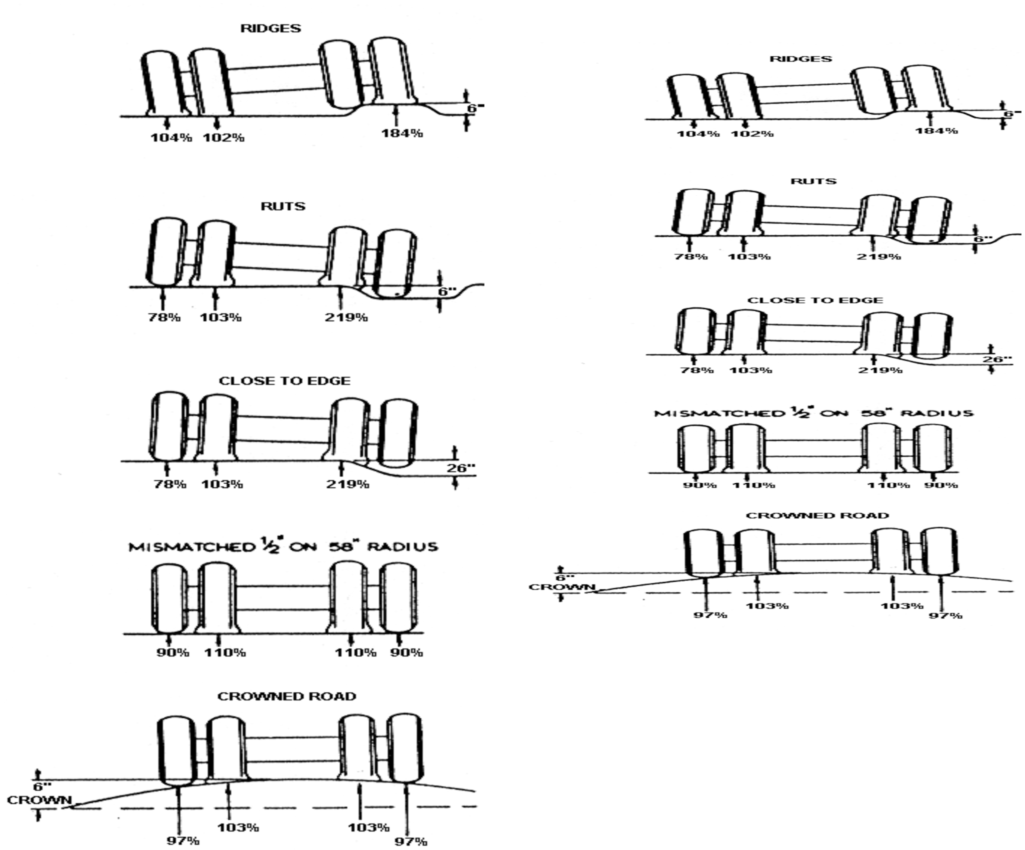



*Figure 2-24: Importance of a Smooth Wearing Course – Reduction in Tyre Life with road Grade and Speed (Woodman & Cutler 1997)*

Roads cannot always be designed matching the ultimate criteria's listed above. Physical constraints need to be taken into consideration, a proposed alignment may require significant rock excavation, and this is when a cost benefit decision should be made. Is it worth shifting a significant amount of rock to ensure a perfectly designed road, or could the speed in a certain area be lowered. What will be the increasing vehicle cycle time over the life of the mine if the speed is decreased? Is this cost greater or less than moving the rock. Many factors are considered when undertaking a road design and generally educated and informed decisions have to be made.

## 2.6.Drainage and Pavement Moisture

A structural pavement design is only as good as the drainage around it. Poor drainage from the road surface leads to saturation of the pavement, potholes, reduced traction and increased fuel consumption (Tannant & Regensburg 2001).

Water that is trapped on the road surface will quickly lead to poor pavement conditions (Thompson 2011b). When the degree of saturation of the unbound pavement exceeds 70% the material may experience significant loss of strength and modulus (Jameson 2012). The aim is to direct water away from the road as quickly as possible without causing erosion. Table drains should be constructed with the invert level deeper than the lowest pavement layer, which prevents seepage into under lying layers (Thompson 2011b).

Precipitation is not the only cause of moisture in a pavement; high groundwater levels in the subgrade may decrease the bearing capacity, cause excessive rutting, high rolling resistance and in high embankments, may cause instability of the road side slope. Should excess water remain in the pavement it may be forced upward by the pumping action of traversing vehicles. This will eventually degrade the bearing capacity of the pavement. This seasonal occurrence can also result in uneven pavement settlement (Tannant & Regensburg 2001).

Another consequence of poor drainage is the wear and tear on the vehicles. A wet running surface increases the likelihood of cuts in tyre treads and sidewalls. The water acts as a lubricant for the rubber and rubber cuts more easily when wet. (Tannant & Regensburg 2001). This can also be caused by overwatering of the haul road.

Therefore when constructing a table drain, Thompson (Thompson 2011b) and Kaufman and Ault (Kaufman & Ault 1977) recommend the typical V Drain characteristics:

- Slope adjacent to the road shoulder should be 4H:1V or flatter and should not exceed 2H:1V.
- The outside slope can vary depending on the ground conditions. In rock it may be vertical, otherwise a 2H:1V or flatter slope is acceptable.
- In a cut / fill section a road cross fall should slope towards the cut side and run drainage in a single table drain.
- In a total cut or total fill situation, slope road crossfall from centreline and run drainage in two table drains.
- With a longitudinal grade between 0% to 4% the drain does not require lining, except in extremely erodible soils.

- With a longitudinal grade over 5%, the table drain should be lined with a course crushed waste rock to a height no less than 0.3m above the maximum depth.
- Where appropriate drains should be constructed with compacted material to prevent as little water as possible from seeping into the underlying layers.

The hydraulic capacity that a table drain is required to hold is determined by the amount of runoff. Hydraulic calculations should be undertaken to assist sizing the drains and cross road culverts. For different catchment analysis methods refer individual mine haul road design manuals or Queensland Urban Drainage Manual (QUDM) (IPWEA 2013).

#### 2.6.1.1. Cross fall

A cross fall ensures water drains freely from the road. Water on a road surface not only damages the pavement it may also cause aquaplaning in very flat terrain. Ideally a cross fall of 2-3% should be adopted (Thompson 2011b). This also assists in not overloading individual tyres as indicated in Figure 2-24.

## 2.7. Maintenance

No matter how well a mine haul road is designed and constructed there will always be a maintenance aspect. The constant traffic that travels the road with heavy loads will deform the surface. This can be controlled through design and appropriate pavement materials; however there will always be the need to schedule maintenance (Kaufman & Ault 1977). The longer road imperfections are left uncorrected, the more likely they are to impede vehicle control and damage machinery.

It is essential that mine haul roads are maintained regularly. However it is really important that preventative procedures are also maximised. A statistic that Thompson mentions in his Haul Road Manual is it takes 500% more time to fix a road that has deteriorated than what it took to originally built it (Thompson 2011b). The major factors that contribute to deterioration of a road surface are weather and vehicles repetitively driving the same path on the haulage lane. These imperfections include but are not limited to dust, potholes, depressions, corrugations, rutting and loose material.

Road deterioration is expensive, not only for fixing the road but also from a machine maintenance point of view. For example, when a tyre encounters a surface imperfection, it will deflect the tyre from its normal direction of travel, the driver must then compensate for this movement by increasing his steering. If this deformation is too great it could result in a complete loss of control. Another example is in dry dusty areas, dust infiltrates brakes, air filters and other critical components of the machine. The result of this is more frequent maintenance (Kaufman & Ault 1977).

Drains should not be forgotten and regularly inspected and cleaned out to remove blockages. Care should also be taken to ensure when grading, a lip is not left on the edge of the road that prevents water from draining away from the surface. Operators are also encouraged to use different parts of the through lane (ie don't always drive in the same spot). Constant concentration of the same path will eventually create ruts or furrows. Spillage from the haul vehicles can also create unnecessary bumps, every effort should be made not to over fill a vehicle (Kaufman & Ault 1977).

Road maintenance is something that is directly related to the location of the mine, its primary goal is to restore the road surface to its original specification. Thompson's manual suggests some routine road maintenance activities to fix imperfections. These include but are not limited to, grading, resurfacing and rehabilitation. Typically there are three ways to go about the maintenance, ad-hoc, scheduled or managed maintenance. However it is unlikely that records are kept showing where and what was done during maintenance. This information would assist with outlining where a road is constantly not performing and if the problem is consistently the same thing (Thompson 2011b).

Thompson suggests that the way to minimise the total overall cost is to minimise the road user costs while maximising the road performance as seen below in Figure 2-25 (Thompson 2011b).

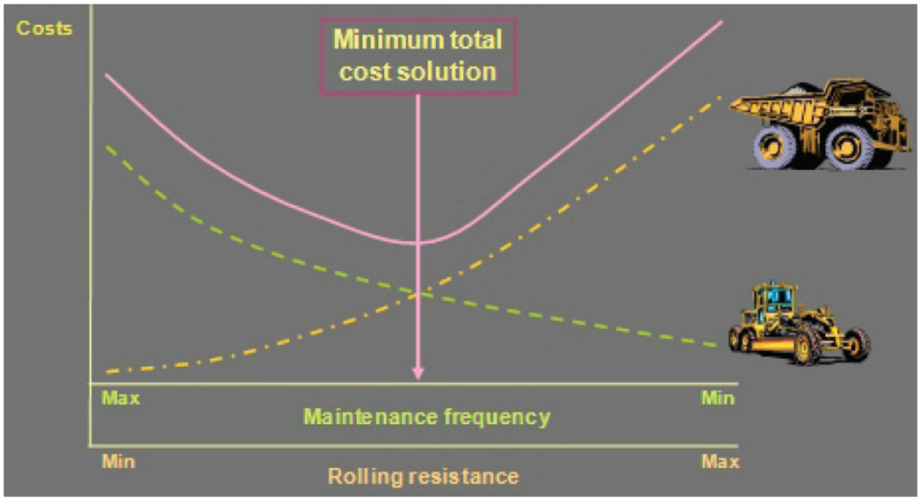



*Figure 2-25: Minimisation of Road Maintenance and Vehicle Operating Costs* (Thompson 2011b)

# CHAPTER 3

# 3. METHODOLGY & CASE STUDIES

This *project* seeks to demonstrate which pavement design method will result in a pavement configuration that will have the least deflection and hence leading performance. This project will use real life scenarios from information obtained from Queensland mine sites.

## 3.1.Background Research and Literature Review

In order to understand all the aspects that combine to produce a pavement design, it was necessary to undertake a literature review. There are many factors that need to be considered when undertaking a pavement design, such as pavement design method, materials used, wearing surface rolling resistance and geometric design. There are multiple sources of information from around the world available for mine haul road design.

## 3.2.Data Sources

Over time there has been three notable public documents produced for mine haul road design, Kaufman and Ault published the first complete document in 1977, their manual included both pavement and geometric design guidelines. In 1996 Roger Thomson undertook his PhD on the design and management of surface mine haul roads. Following on from his PhD, Roger has published numerous documents relating to haul road design. These have covered everything from the design, construction, maintenance and associated costs and how to minimise costs while delivering a well-designed road. In between Thompson’s thesis and his mine haul road manual in 2011, Tannant and Regensburg published a guideline to mine haul road design in 2001. Their guideline information was developed from the surface mines in Western Canada. While every effort was made to use these sources, other sources were perused to support or further investigate their claims.

Two major mining companies that have multiple mining operations within Australia have also developed their own haul road design manuals. BMA have two manuals, the latest one published in 2012 which supersedes their first manual from 1998 and RioTinto have their own manual that was produced in 2004. The majority of the information supplied in these manuals refers back to either Kaufman and Ault, Thompson or Tannant and Regensburg's manuals.

## 3.3. Case Studies

The various aspects discussed within the literature review will be utilised to undertake two case studies. The desired outcome would be the identification of one pavement design method that is cost effective and produces the least deflection of the wearing course. This method can then be recommended for pavement designs within the mining industry.

Due to confidentiality mine site specific information cannot be disclosed. For the purposes of this study all information obtained will be referred to as Mine Site A and Mine Site B. Both mine sites are located within the Bowen Basin. The Bowen Basin is a coal and gas rich area with the largest coal reserve in Australia. Figure 3-1 illustrates the area and mines within the Bowen Basin. The deposit contains one of the largest deposits of bituminous coal within the world. The area covers over 60,000 square kilometres within Central Queensland with the northern most mine near Collinsville and southern most mine near Moura. (Rolfe 2011a)

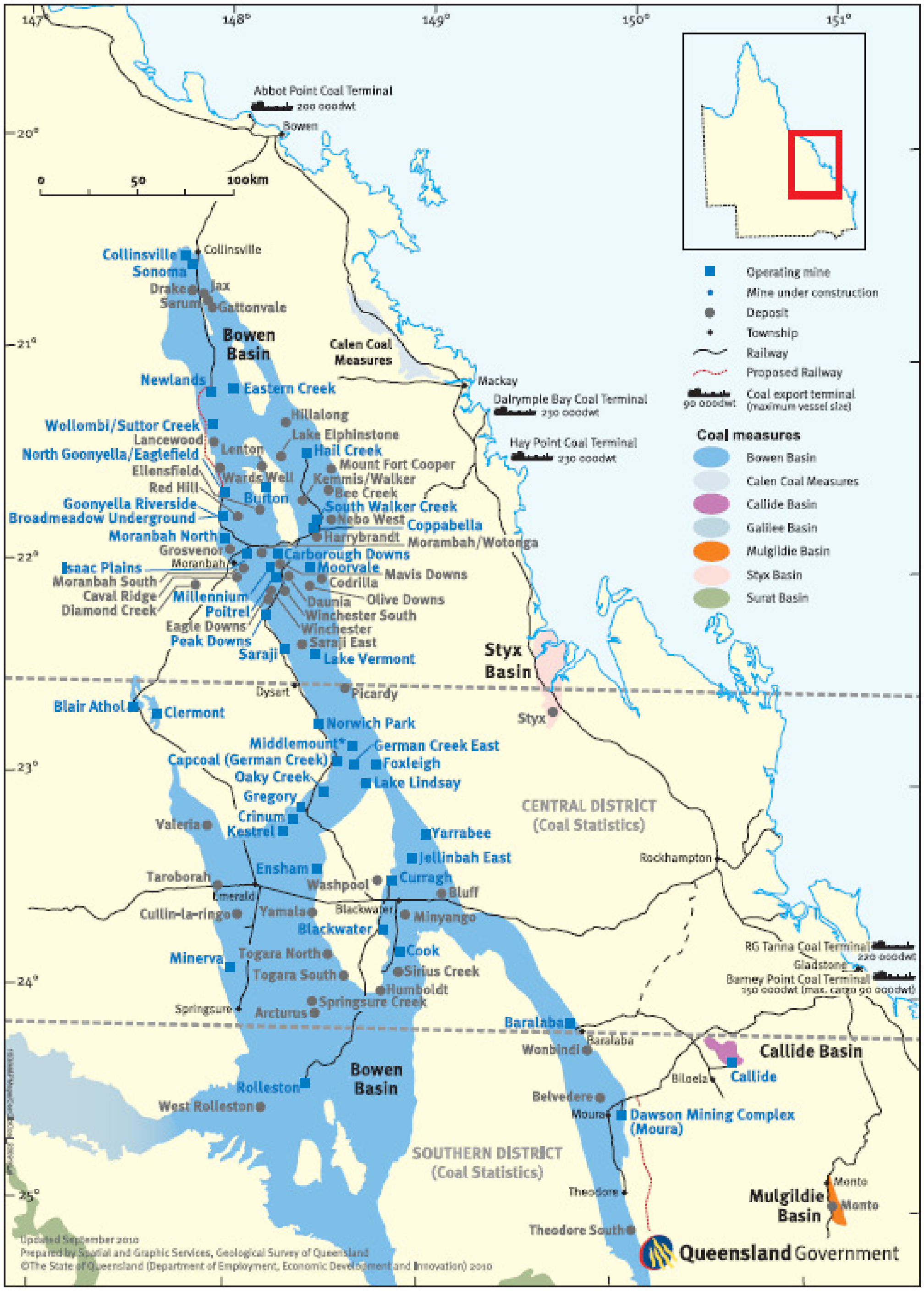



*Figure 3-1: Bowen Basin Mines (Bowen Basin Coal Mines 2000)*

## 3.4.Pavement Material Cost

All rates listed in Table 3-1 have been obtained from industry representatives in August 2015 and are indicative only for the purposes of this *project*. All rates include supply, spread, trim and compaction. These rates will be utilised for both Case Study A and Case Study B. It is acknowledged when these mines were constructed the rates would have been considerably different; however for the purpose of a comparison these rates are considered suitable.

*Table 3-1: Pavement Material Rates per Cubic Metre*

| **Pavement Material Cost** | | | |
|---|---|---|---|
| **Material Type** | **CBR** | **Modulus (MPa)** | **Rate ($/m$^3$)** |
| 2.1 | 80 | 350 | 160 |
| 2.2 | 60 | 290 | 135 |
| 2.3 | 45 | 240 | 125 |
| 2.4 | 35 | 206 | 120 |
| 2.5 | 15 | 120 | 110 |
| 2% Cement Modified 2.1 | | 500 | 195 |
| 2% Cement Modified 2.1 | | 400 | 170 |
| Blast Rock | | 3000 | 140 plus $10/m$^2$ for geo-fabric |

## 3.5. Case Study A – Mine Site A

### 3.5.1. Background Information

Mine Site A is located within the Central District of the Bowen Basin and produces both coking coal and thermal coal that is exported to Japan, Asia, South America, Europe and the Middle East. Mine Site A is a large scale mine that produces over 10 million tonnes per annum. Their current fleet of Haul Vehicles include Kress 200C Coal Haulers and Cat 793. (Rolfe 2011b)

Mine Site A had a unique problem their truck park up area requires relocation and expanding. The chosen location is close to the Coal Handling Preparation Plant (CHPP) and is on a loop road that is currently utilised for refuelling purposes.

### 3.5.2. Geotechnical Investigation

Geotechnical investigations identified that the area was relatively flat with a slight fall towards the east and south. Numerous depressions around the site alluded to poor drainage and maintenance.

It was proposed that the geotechnical engineer would excavate and examine four pits however due to access restrictions imposed by mine management, only two pits were examined. Visual classification and laboratory tests including sieve analysis, Atterberg limits, linear shrinkage and CBR were undertaken.

Results included that a subgrade CBR of 5% would be appropriate assuming the existing sandy clayey gravel fill will perform. Subgrade preparation should include:

- Removal of surficial cohesive soil pockets to expose the gravel fill
- Reworking the exposed gravel fill to remove over size fractions (>100mm size) and foreign matter
- Moisture conditioning the reworked material and then compacting the subgrade to a minimum of 100% standard dry density ratio.

### 3.5.3. Case Study A - Issued for Construction Information

The following information is the design that has been specified on the engineering design drawings and pavement option 3 presented in Figure 3-2 has been constructed onsite.

## PAVEMENT DESIGN OPTIONS

### PAVEMENT OPTION 1
- 200mm WEARING COURSE
- 300mm CBR 80 BASE GRAVEL
- 300mm CBR 45 SUBBASE GRAVEL
- 600mm CBR 15 LOWER SUBBASE GRAVEL

- DESIGN SUBGRADE CBR 8
- DESIGN VEHICLE: CAT 793 (LOADED)

### PAVEMENT OPTION 2
- 200mm WEARING COURSE
- 200mm CBR 80 BASE GRAVEL
- 200mm CBR 45 SUBBASE GRAVEL
- 500mm CBR 15 LOWER SUBBASE GRAVEL

- DESIGN SUBGRADE CBR 8
- DESIGN VEHICLE: CAT 793 (EMPTY)

### PAVEMENT OPTION 3
- 200mm WEARING COURSE
- 300mm CBR 15 LOWER SUBBASE GRAVEL

- DESIGN SUBGRADE CBR 8
- DESIGN VEHICLE: CAT 777 (EMPTY)

### WEARING COURSE MATERIAL
- CBR = 50MIN
- GRADING

| | |
|---|---|
| 37.5mm | 95–100 |
| 26.5mm | 90–100 |
| 19mm | 80–100 |
| 2.36mm | 35–65 |
| 0.425mm | 15–50 |
| 0.075mm | 10–40 |
| MAX PI = 12 | |

### NOTES:
1. ALL PAVEMENT MATERIALS COMPACTED TO MIN 97% STANDARD
2. SUBGRADE MATERIAL TYNE UP, MOISTURE CONDITION AND COMPACT 300mm DEEP LAYER TO 95% STANDARD.
3. IF CORRECTOR COURSE IS NEEDED USE SAME MATERIAL AS WEARING COURSE.

*Figure 3-2: Case Study A – Issued For Construction Pavement Design Configurations*

### 3.5.4. Design Vehicle Information

The information presented within Table 3-2 outlines the design criteria used when developing the issued for construction pavement design.

*Table 3-2: Mine Site A Relevant Design Vehicle Information*

| | **Kress 200C** (Corporation 2004) | **Cat 793** (Caterpillar 2010b) |
|---|---|---|
| **Engine** | Cat 3512B HD Electronic Unit Injection Engine | Cat C175-16 |
| **Machine Weight** | 148 Tonne | 170 Tonne |
| **Nominal Payload Weight** | 220 Tonne | 220 Tonne |
| **Gross Machine Weight** | 368 Tonne | 390 Tonne |
| **Weight Distribution** | Front Axle – Empty 43.5%<br>Rear Axle – Empty 56.5%<br>Front Axle – Loaded 51%<br>Rear Axle – Loaded 49% | Front Axle – Empty 48%<br>Rear Axle – Empty 52%<br>Front Axle – Loaded 33%<br>Rear Axle – Loaded 67% |
| **Tyres** | 36.00 R 51 | 40.00 R 57 |
| **Tyre Diameter** | 3233mm | 3569mm |
| **Tyre Width** | 988mm | 1130mm |
| **Tyre Pressure (KPa)** | 700 | 700 |
| **Wheel Load (tonne)** | 46 | 65 |
| **ESWL (20% of Wheel Load)** | 55.2 | 78 |

As the Cat 793 is heavier than the Kress 200C all pavement designs will be calculated using the Cat 793, refer Figure 3-3 for typical Cat 793 vehicle dimensions. The gross vehicle weight is 390 tonne, therefore the wheel load is 65 tonne and ESWL 78 tonne (20% increase).

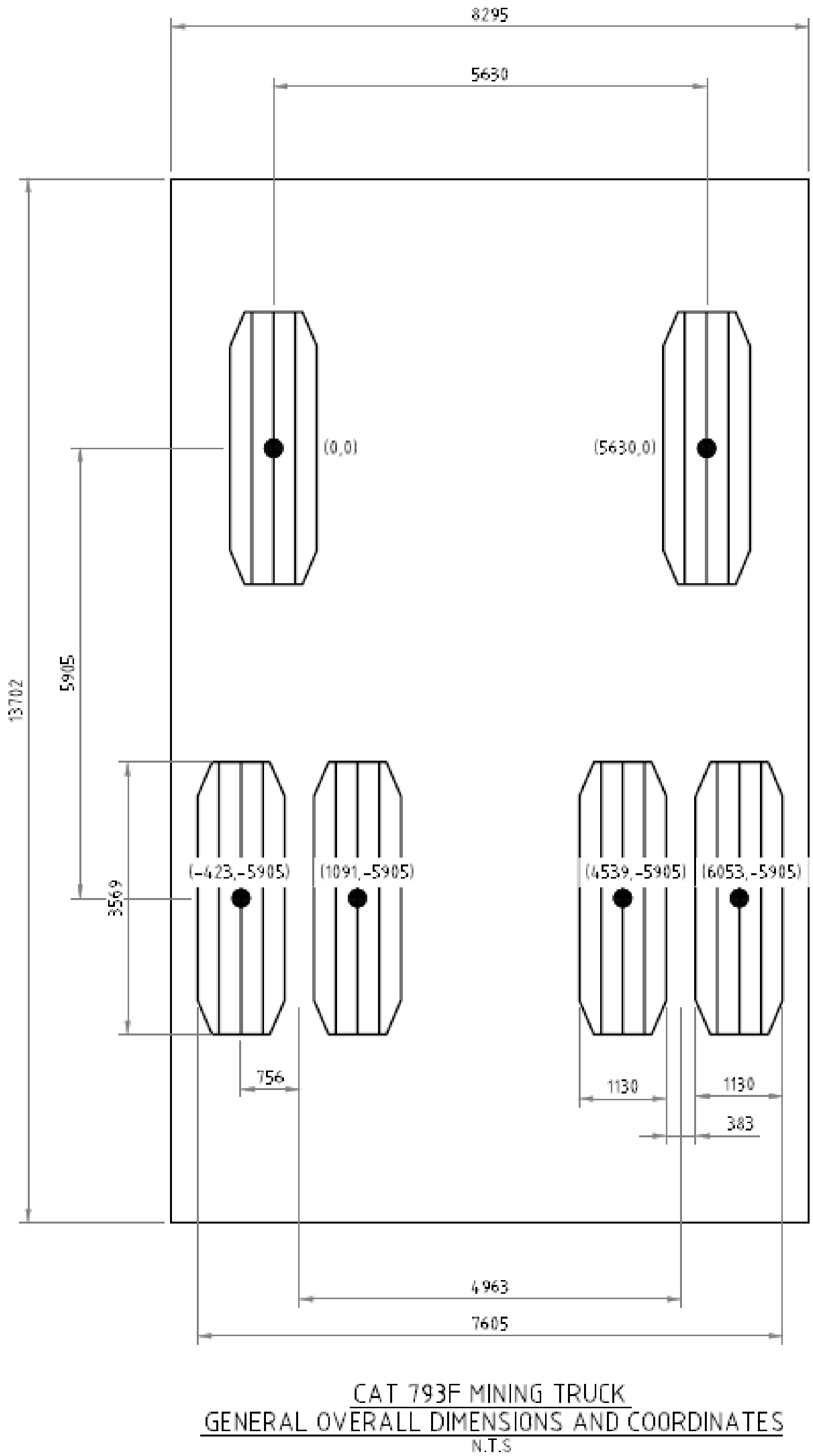



*Figure 3-3: CAT 793F Mining Truck General Overall Dimensions and CIRCLY Coordinates (Caterpillar 2010b)*

Using the same parameters the pavement will be designed using the different methods as described in Section 2.1 Pavement Design to determine how the total thickness and configurations will vary and how they will affect the overall deflection.

### 3.5.5. Traffic Calculation

If the mine produces 10 million tonne of coal per annum they are processing approximately 14.3 million tonne of raw material. For the purpose of this *project*, it is assumed that the coal processing plant is located centrally within the mine. Therefore approximately 7.2 million tonne is being transported from each end of the mine. A Cat 793 / Kress 200C is capable of carrying 220 tonne of material each load therefore annually there will be 32850 loads (90 / Day). Over the design life of the mine (assume 20 years) it is expected that the haul road design traffic will be 657,000 movements.

### 3.5.6. Subgrade Performance

Due to the large vehicle loads and a high number of vehicle movements it has been assumed that the subgrade may not behave linearly. Therefore Equation 2-12 and Equation 2-13 from Section 2.1.7 should be used to calculate the subgrade material constant and material damage exponent.

$$k = (1.64 \times 10^{-9} \times E^3) - (4.31 \times 10^{-7} \times E^2) + (2.18 \times 10^{-5} \times E) + 0.00289$$

*Equation 2-12*

Where $E = subgrade\ modulus\ (MPa; Usually\ expressed\ as\ 10 \times CBR)$

*Equation 2-14*

$$k = (1.64 \times 10^{-9} \times 50^3) - (4.31 \times 10^{-7} \times 50^2) + (2.18 \times 10^{-5} \times 50) + 0.00289$$

$$k = 0.0031$$

$$b = (-2.12 \times 10^{-7} \times E^3) + (8.38 \times 10^{-4} \times E^2) - (0.0274 \times E) + 9.57$$

*Equation 2-13*

$$b = (-2.12 \times 10^{-7} \times 50^3) + (8.38 \times 10^{-4} \times 50^2) - (0.0274 \times 50) + 9.57$$

$$b = 10.2685$$

### 3.5.7. Case Study A Pavement Designs A.1 – Fully Loaded Vehicle

#### 3.5.7.1. Pavement Design A.1.1 – Ahlvins Method

Applying Ahlvins method: using Equation 2-6:

$$t = \sqrt{A}\left(-0.048 - 1.1562\left(log\frac{CBR}{Pe}\right) - 0.6414\left(log\frac{CBR}{Pe}\right)^2 - 0.4730\left(log\frac{CBR}{Pe}\right)^3\right)$$

*Equation 2-6*

t = Thickness of overlying layer (m)

Load = 65 Tonne

ESWL = 78 Tonne

Tyre Pressure = 700 kPa

$$A = \frac{load}{tyre\ pressure}$$

$$A = \frac{65}{700}$$

$$A = 0.093$$

$$P_e = \frac{ESWL}{Area}$$

$$P_e = \frac{78}{0.093}$$

$$Pe = 840$$

*CBR = Subgrade CBR 5%*

$$t = \sqrt{0.093}\left(-0.048 - 1.1562\left(log\frac{5}{840}\right) - 0.6414\left(log\frac{5}{840}\right)^2 - 0.4730\left(log\frac{5}{840}\right)^3\right)$$

$$t = 1.38\ \therefore 1.40m$$

Therefore use total pavement thickness of 1.4m.

*CBR = Lower Subbase CBR 15%*

$$t = \sqrt{0.093}\left(-0.048 - 1.1562\left(log\frac{15}{840}\right) - 0.6414\left(log\frac{15}{840}\right)^2 - 0.4730\left(log\frac{15}{840}\right)^3\right)$$

$$t = 0.77\ \therefore 0.8m$$

Therefore use a 600mm CBR 15 layer.

*CBR = Upper Subbase CBR 35%*

$$t = \sqrt{0.093}\left(-0.048 - 1.1562\left(log\frac{35}{840}\right) - 0.6414\left(log\frac{35}{840}\right)^2 - 0.4730\left(log\frac{35}{840}\right)^3\right)$$

$t = 0.47 \;\therefore 0.5m$

Therefore use a 300mm CBR 35 layer.

*CBR = Base CBR 80%*

$$t = \sqrt{0.093}\left(-0.048 - 1.1562\left(log\frac{80}{840}\right) - 0.6414\left(log\frac{80}{840}\right)^2 - 0.4730\left(log\frac{80}{840}\right)^3\right)$$

$t = 0.29 \;\therefore 0.3m$

Therefore use a 300mm CBR 80 layer.

*CBR = Wearing Course CBR 80%*

Overall remaining layer will be a 200mm CBR 80.

Refer Figure 3-4 for configuration.

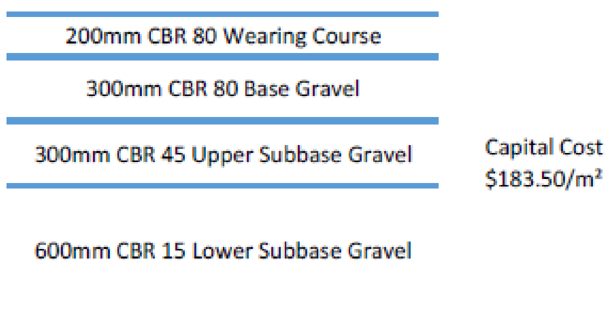



*Figure 3-4: Mine Site A – Pavement Design Configuration Option A.1.1 (IFC Specified Design)*

#### 3.5.7.1. Pavement Design A.1.2 – Thompsons Formula

Kaufman and Ault's (Kaufman & Ault 1977) design charts do not cater for vehicles wheel loads larger than 55 tonne therefore Equation 2-1 from Thompsons Haul Road Design Manual will be used as a substitute.

$$z_{CBR} = \frac{9.81t_w}{P}\left[0.104 + 0.331e^{(-0.0287t_w)}\right]\left[2 \times 10^{-5\left(\frac{CBR}{P}\right)}\right]\left[\left(\frac{CBR}{P}\right)^{-\left(0.415+P\times10^{-4}\right)}\right]$$

*Equation 2-1*

| | | |
|---|---|---|
| $Z_{CBR}$ | = | Thickness of overlying layer (m) |
| $T_w$ | = | Truck wheel load |
| P | = | Tyre pressure (kPa) |
| CBR | = | California Bearing Ratio of the material (%) |

*CBR = Subgrade CBR 5%*

$$z_{CBR} = \frac{9.81 \times 78}{700}\left[0.104 + 0.331e^{(-0.0287\times78)}\right]\left[2 \times 10^{-5\left(\frac{5}{700}\right)}\right]\left[\left(\frac{5}{700}\right)^{-\left(0.415+700\times10^{-4}\right)}\right]$$

$z_{CBR} = 1.54 \;\therefore 1.55m$

Therefore use total pavement thickness of 1.55m.

*CBR = Lower Subbase CBR 15%*

$$z_{CBR} = \frac{9.81 \times 78}{700}\left[0.104 + 0.331e^{(-0.0287\times78)}\right]\left[2 \times 10^{-5\left(\frac{15}{700}\right)}\right]\left[\left(\frac{15}{700}\right)^{-\left(0.415+700\times10^{-4}\right)}\right]$$

$z_{CBR} = 0.9m$

Therefore use a 650mm CBR 15 layer.

*CBR = Upper Subbase CBR 35%*

$$z_{CBR} = \frac{9.81 \times 78}{700}\left[0.104 + 0.331e^{(-0.0287\times78)}\right]\left[2 \times 10^{-5\left(\frac{35}{700}\right)}\right]\left[\left(\frac{35}{700}\right)^{-\left(0.415+700\times10^{-4}\right)}\right]$$

$z_{CBR} = 0.48 \;\therefore 0.5m$

Therefore use a 400mm CBR 35 layer.

*CBR = Base CBR 80%*

$$z_{CBR} = \frac{9.81 \times 78}{700}\left[0.104 + 0.331e^{(-0.0287\times78)}\right]\left[2 \times 10^{-5\left(\frac{80}{700}\right)}\right]\left[\left(\frac{80}{700}\right)^{-\left(0.415+700\times10^{-4}\right)}\right]$$

$z_{CBR} = 0.17 \;\therefore 0.2m$

Therefore use a 300mm CBR 80 layer.

*CBR = Wearing Course CBR 80%*

Overall remaining layer will be a 200mm CBR 80.

Figure 3-5 below also replicates Equation 2-1. Using this method the total thickness is equivalent 1.55m, refer Figure 3-6 for configuration details.

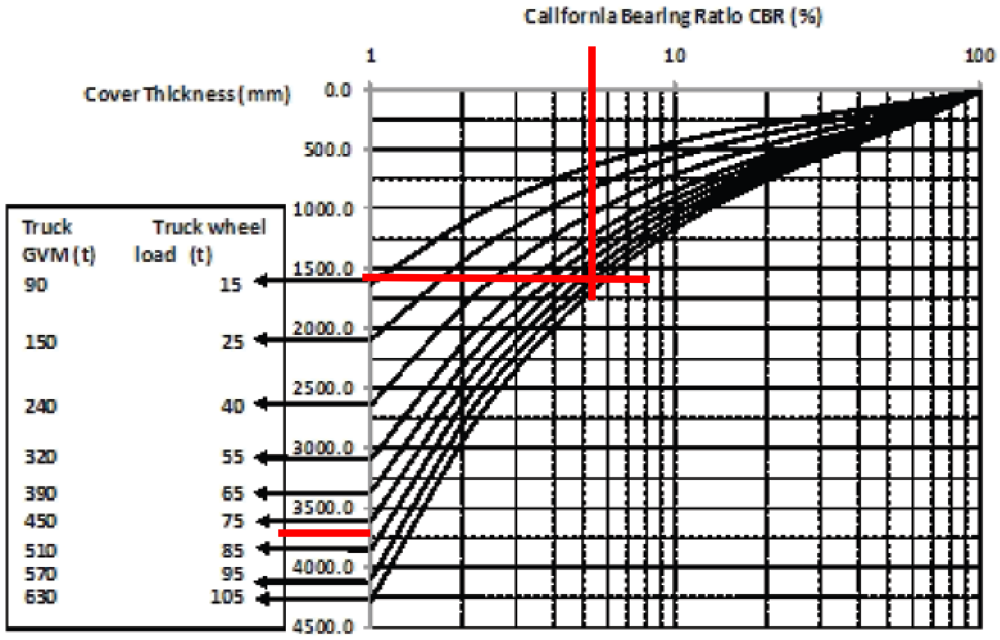



*Figure 3-5: Thompson's CBR Cover-Curve Design Chart – Pavement Design A.1.2*

Refer Figure 3-6 for pavement configuration.

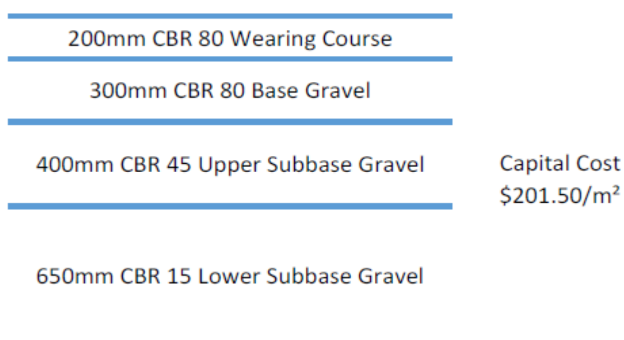



*Figure 3-6: Mine Site A – Pavement Design Configuration Option A.1.2*

#### 3.5.7.1. Pavement Design A.1.3 – Ahlvin Method (Austroads Sublayering)

Using Equation 2-9 calculate the modulus at the top of the first equi-thick layer.

$$E_{v\,(top\ granular\ sublayer)} = E_{v\ underlying\ material} \times 2^{(total\ granular\ thickness/125)}$$

*Equation 2-9*

$$E_{v\,(top\ granular\ sublayer)} = 50 \times 2^{\left(\frac{280}{125}\right)}$$

$$E_{v\,(top\ granular\ sublayer)} = 236.3\ \therefore \text{Use 150 as defined in Table 21}$$

$$R = \left[\frac{E_{v\ top\ granular\ sublayer}}{E_{underlying\ material}}\right]^{\frac{1}{5}}$$

*Equation 2-10*

$$R = \left[\frac{150}{50}\right]^{\frac{1}{5}}$$

$R = 1.245$

Modulus of sublayer 2 = $150 \times 1.245 = 186MPa$

Modulus of sublayer 3 = $186 \times 1.245 = 230MPa$

Modulus of sublayer 4 = $230 \times 1.245 = 285MPa$

Modulus of sublayer 5 = $285 \times 1.245 = 354MPa$

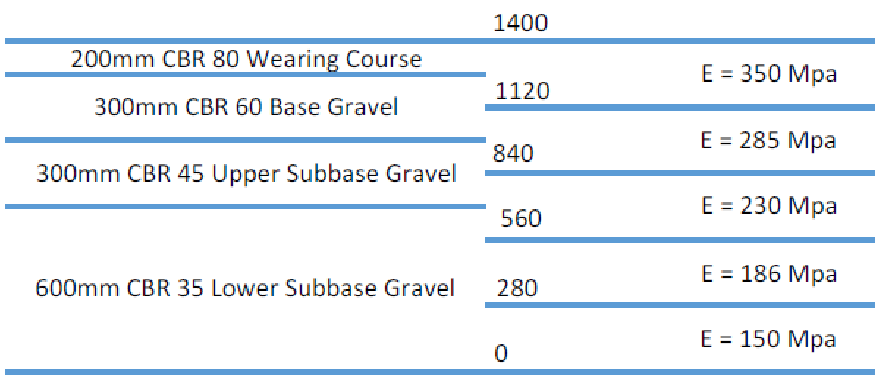



*Figure 3-7: Austroads Equi-thick Sub-layering Option A.1.3*

Therefore to ensure the vertical modulus for each sublayer does not exceed the maximum modulus the granular material in the sublayer can develop, the base course will be CBR 80, subbase CBR 60, upper subbase CBR 45 and lower subbase CBR 35. Refer Figure 3-8 for pavement configuration.

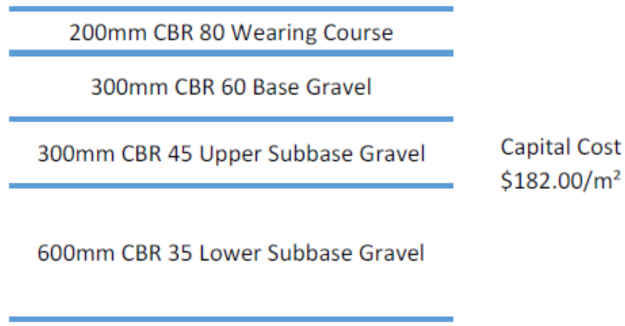



*Figure 3-8: Mine Site A – Pavement Design Configuration Option A.1.3*

#### 3.5.7.2. Pavement Design A.1.4 - Thompsons Blast Rock Method

To use Thompsons Blast Rock Method firstly it must be decided what category of road is being designed. Using Figure 2-8 this pavement will be designed for a Category I – permanent life of mine with high traffic volume and an operating life greater than 20 years. Therefore the vertical elastic strains will be limited to 900 microstrains.

Using Equation 2-8 the resilient modulus input is:

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

*Equation 2-8*

$$E_{eff} = 17.63 \times 5^{0.64}$$

$$E_{eff} = 49.38\ MPa$$

Reading the chart in Figure 3-9: Cat 793D Base Layer Thickness Design ChartFigure 3-9 the total thickness of the base layer will be 830mm, resulting in a total pavement configuration thickness of 1030mm. Refer Figure 3-10 for pavement configuration..

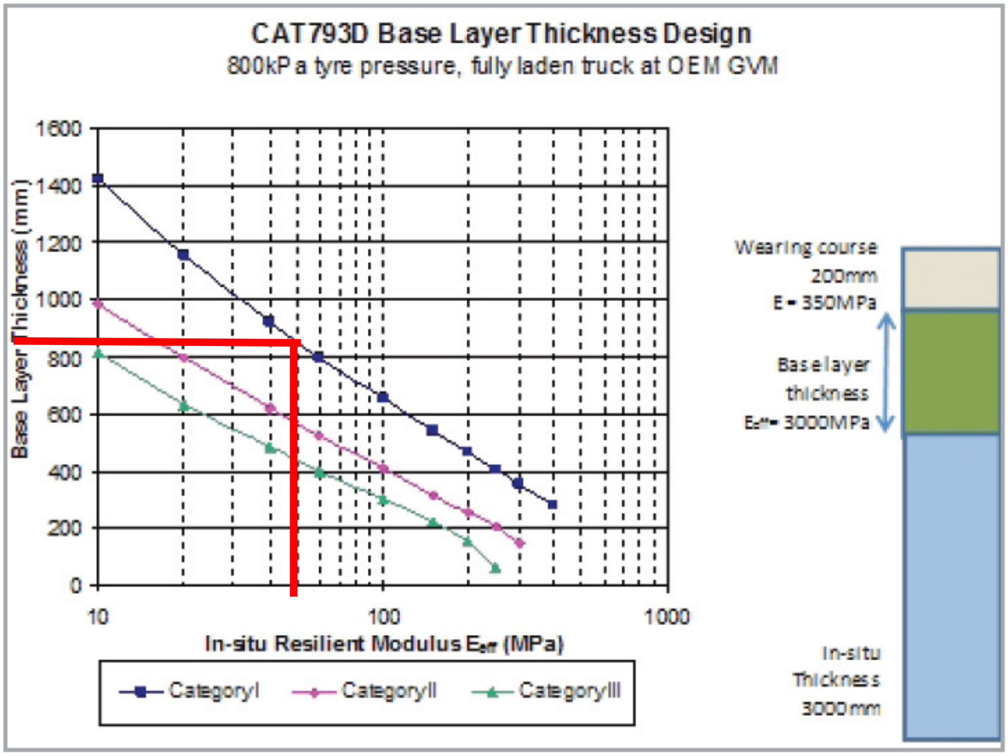



*Figure 3-9: Cat 793D Base Layer Thickness Design Chart*

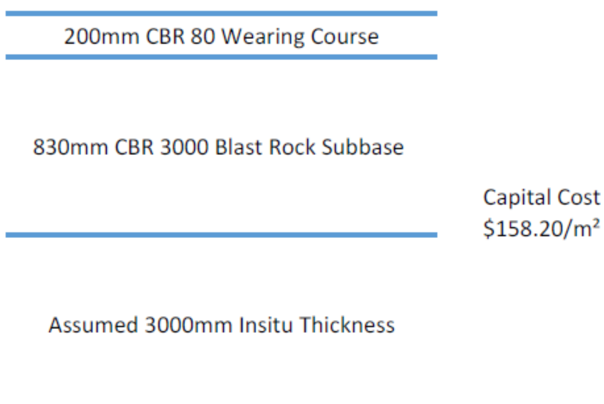



*Figure 3-10: Mine Site A – Pavement Design Configuration Option A.1.4*

#### 3.5.7.1. Pavement Design A.1.5 - Ahlvin Method (Austroads Sublayering) with Improved Subbase

In an effort to try and improve the overall deflection the subgrade could be lime stabilised to achieve a design CBR of 15. It has been assumed that the maximum depth that can be stabilised at once is 500mm therefore other layers have been adjusted to reflect this. Testing would be required to determine the required lime stabilisation percentage. Refer Figure 3-11 for pavement configuration.

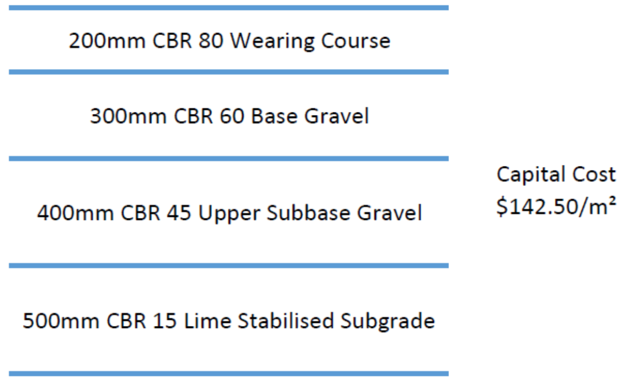



*Figure 3-11: Mine Site A – Pavement Design Configuration Option A.1.5*

#### 3.5.7.2. Pavement Design A.1.6 - Cement Modified Base Materials

In another effort to try and improve the overall deflection the base and subbase gravels could be 2% cement stabilised to achieve a design CBR of 500 and CBR 400 respectively. High strength materials (400 and 500 MPa) are not available within Queensland without cement stabilisation. Refer Figure 3-12 for pavement configuration.

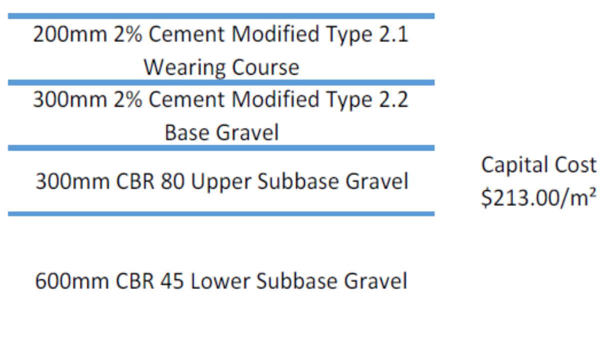



*Figure 3-12: Mine Site A – Pavement Design Configuration Option A.1.6*

#### 3.5.7.3. Pavement Design A.1.7 - Ahlvin Method (Austroads Sublayering) with CDF 1

A test was undertaken to determine if having a cumulative damage factor of 1 resulted in significantly less deflection. Using CIRCLY the base layer was increased until the CDF factor equalled 1. This resulted in an overall pavement thickness of 2.38m. Refer Figure 3-13 for pavement configuration.

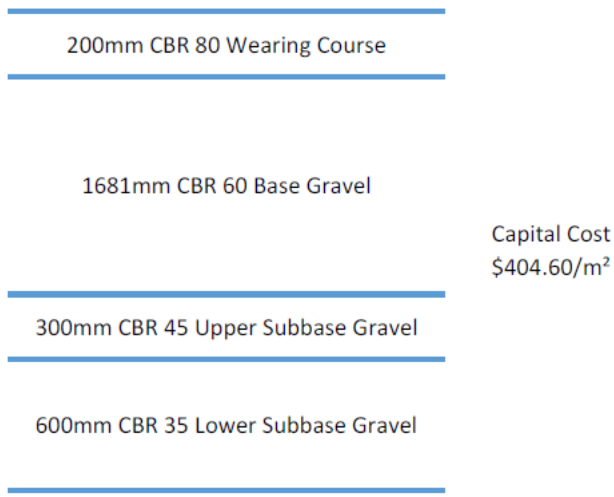



*Figure 3-13: Mine Site A – Pavement Design Configuration Option A.1.7*

#### 3.5.7.1. Pavement Design A.1.8 - Ahlvin Method (Austroads Sublayering) with Anisotropic Materials

One final pavement configuration was run to determine how much the deflection varied dependent on whether the pavement was modelled with isotropic or anisotropic materials. Ahlvin's method with Austroads sublayering (Refer Figure 3-8) has performed the best to date and appears to be the cost effective so this configuration was chosen for a comparison.

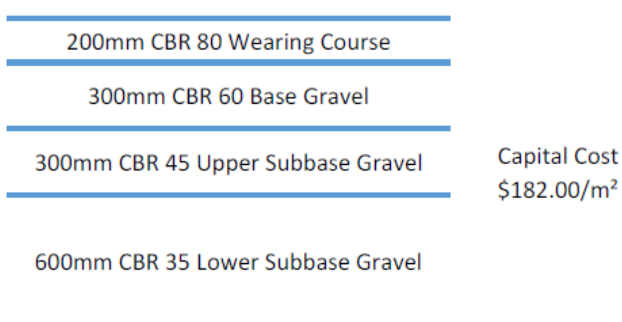



*Figure 3-14: Mine Site A – Pavement Design Configuration Option A.1.8*

### 3.5.8. Case Study A Pavement Designs A.2 – Unloaded Vehicle

Mine site A decided that they could not afford the capital cost to construct the desired pavement configuration specified (Option A.1.1). Instead Mine Site A wanted an analysis undertaken to determine the difference in pavement configuration if only an unloaded truck was driven over the pavement. Due to the fuel bay being on this loop it was also imperative that only unloaded trucks were driven on the pavement to obtain fuel.

The weight of an unloaded Cat 793 is 170 tonne, therefore the wheel load is 28.3 tonne and ESWL 33.96 tonne (20% increase).

Using the same calculations as described in section 3.5.7. The following configurations were derived.

#### 3.5.8.1. Pavement Design A.2.1 – Ahlvins Method

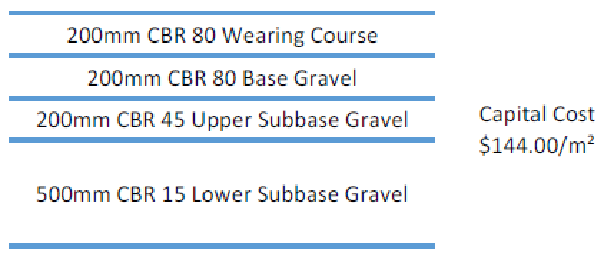



*Figure 3-15: Mine Site A – Pavement Design Configuration Option A.2.1 (IFC Specified Design)*

#### 3.5.8.2. Pavement Design A.2.2 – Thompsons Formula

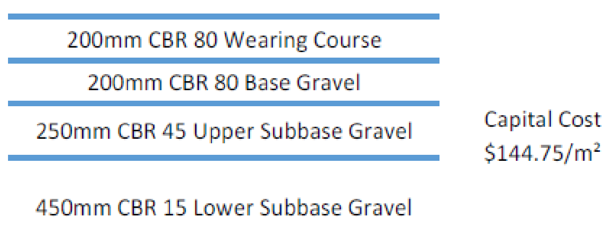



*Figure 3-16: Mine Site A – Pavement Design Configuration Option A.2.2*

#### 3.5.8.3. Pavement Design A.2.3 – Ahlvins Method (Austroads Sublayering)

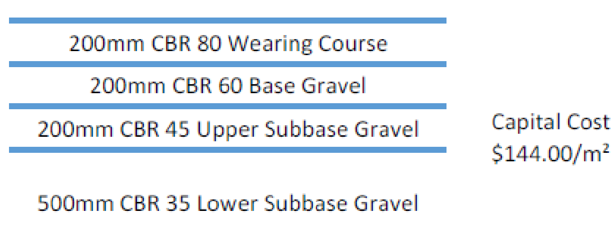



*Figure 3-17: Mine Site A – Pavement Design Configuration Option A.2.3*

#### 3.5.8.4. Pavement Design A.2.4 – Ahlvins Method (Austroads Sublayering) with Improved Subbase

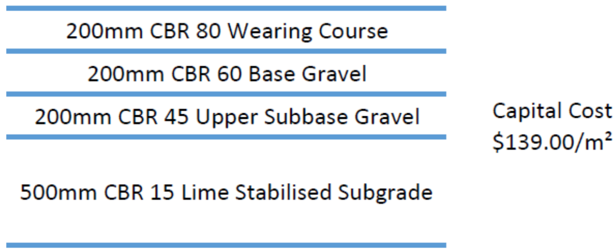



*Figure 3-18: Mine Site A – Pavement Design Configuration Option A.2.4*

#### 3.5.8.5. Pavement Design A.2.5 - Cement Modified Base Materials

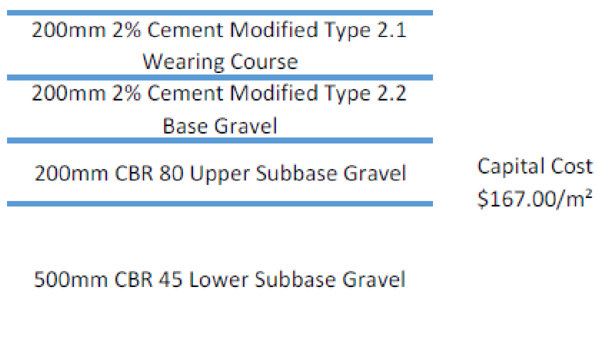



*Figure 3-19: Mine Site A – Pavement Design Configuration Option A.2.5*

### 3.5.9. Case Study A Pavement Design A.3 – Client Requested Configuration

Mine Site A was still adamant that due to budget constraints the 1.1m thick pavement configuration could not be constructed. Therefore they requested that only 500mm of pavement be installed. To achieve this a 200mm CBR 80 wearing course was used with a 300mm CBR 15 base. Refer Figure 3-20 for configuration details.

#### 3.5.9.1. Pavement Design A.3.1

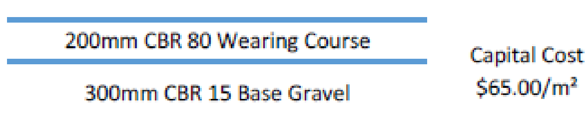



*Figure 3-20: Mine Site A – Pavement Design Configuration Option A.3.1 (IFC Specified Design)*

Not only is deflection a concern here overall performance will be compromised as soon as the pavement becomes saturated.

### 3.5.1. Case Study A Maximum Deflections

All pavement designs for Case Study A.1 were run through CIRCLY to determine how the different configurations affected the maximum deflection. The results are displayed in Figure 3-21 and Figure 3-22.

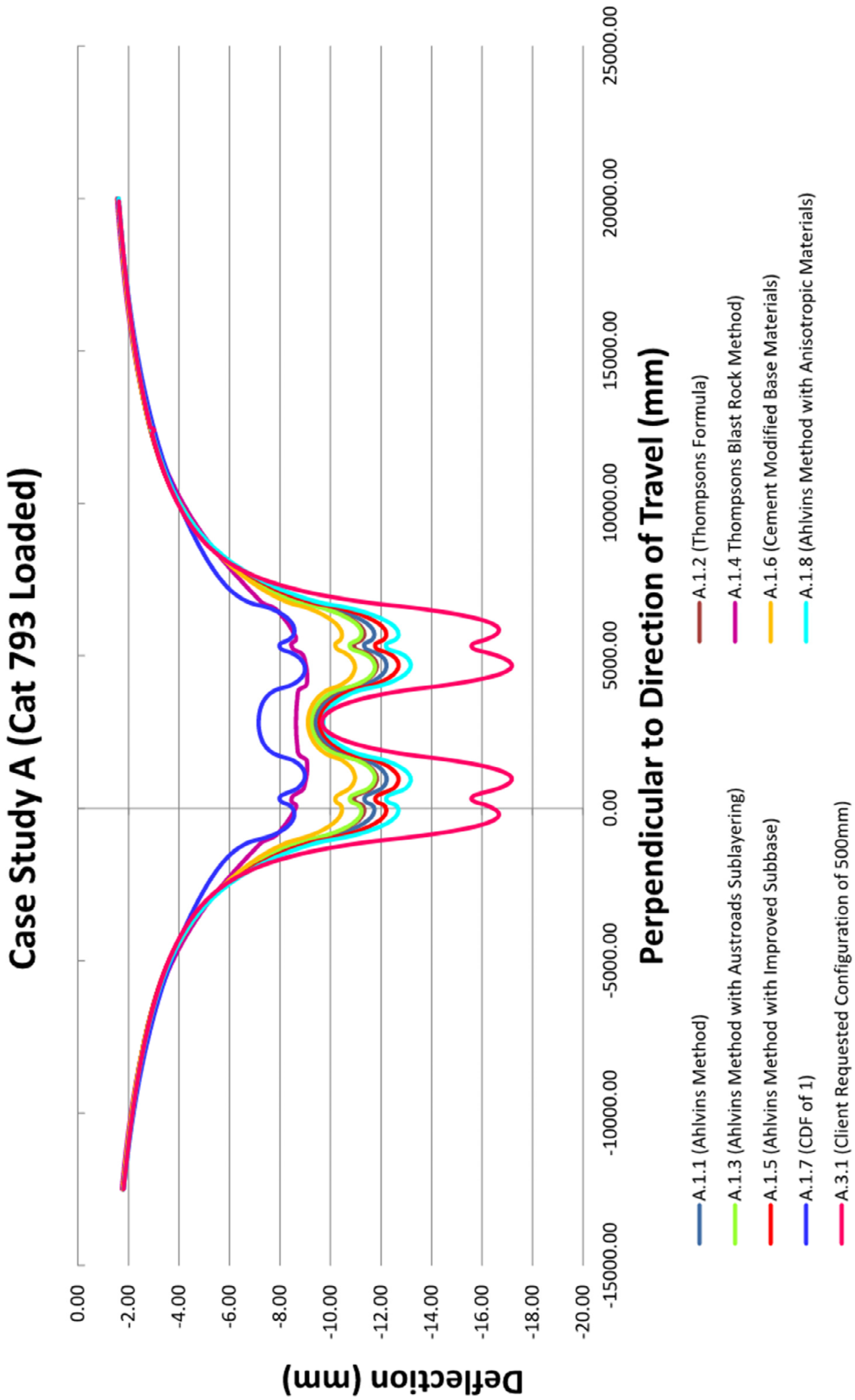



*Figure 3-21: Case Study A.1 & A.3 Cat 793 Fully Loaded Maximum Deflections*

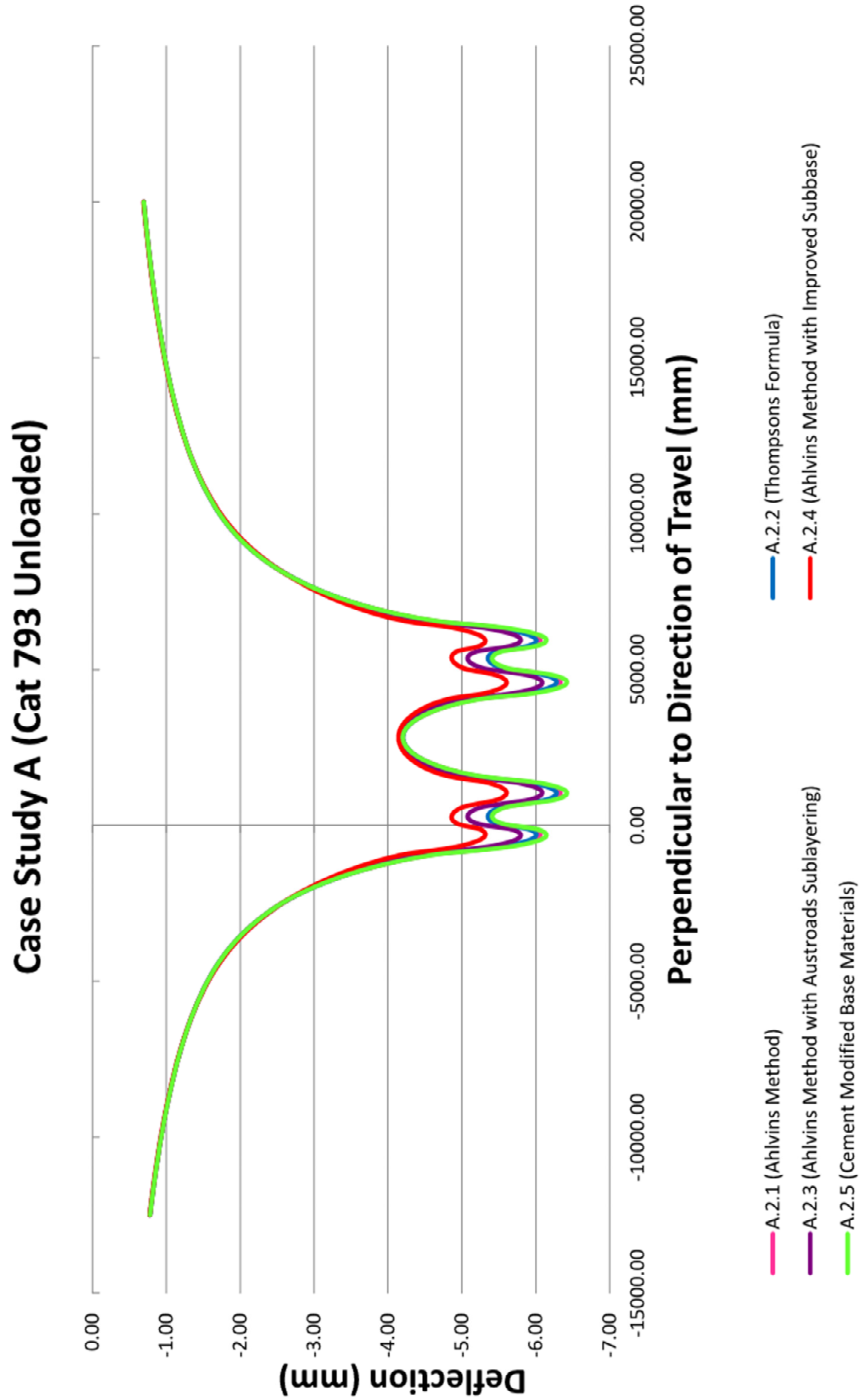



*Figure 3-22: Case Study A.2 Cat 793 Unloaded Maximum Deflections*

*Table 3-3: Case Study A Maximum Deflection Values*

| Pavement Design Option | Total Configuration Thickness | Capital Cost ($/m2) | Maximum Deflection (mm) |
|---|---|---|---|
| | **Case Study A Option A.1** | | |
| A.1.1 | 1400 | $184.50 | 12.22 |
| A.1.2 | 1550 | $201.50 | 11.84 |
| A.1.3 | 1400 | $182.00 | 11.76 |
| A.1.4 | 1030 | $158.20 | 9.05 |
| A.1.5 | 1400 | $142.50 | 12.69 |
| A.1.6 | 1400 | $213.00 | 10.97 |
| A.1.7 | 3000 | $404.59 | 8.98 |
| A.1.8 | 1400 | $182.00 | 13.13 |
| | **Case Study A Option A.2** | | |
| A.2.1 | 1100 | $144.00 | 6.33 |
| A.2.2 | 1100 | $144.75 | 6.27 |
| A.2.3 | 1100 | $144.00 | 6.08 |
| A.2.4 | 1100 | $167.00 | 5.60 |
| A.2.5 | 1100 | $139.00 | 6.42 |
| | **Case Study A Option A.2** | | |
| Option A.3.1 | 500 | $65.00 | 17.17 |

## 3.6. Case Study B - Mine Site B

### 3.6.1. Background Information

Mine Site B is located within the Central District of the Bowen Basin and produces thermal coal that is exported to Asia, Europe and sold domestically. Mine Site B is a large scale mine that produces over 10 million tonnes per annum.

### 3.6.2. Geotechnical Information

A geotechnical report for this site was not available. Instead one as constructed drawing provided the following information, another plan indicated that the design subgrade CBR is 5%:

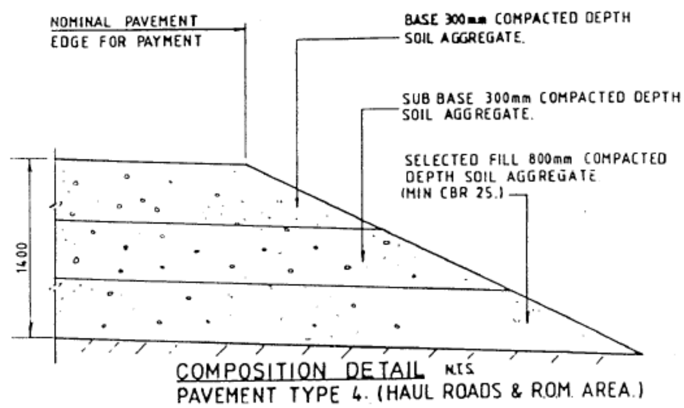



*Figure 3-23: Case Study B - As-Constructed Information*

This configuration was used to determine if under different load conditions the pavement methods resulted in similar results as Case Study A. This will allow a conclusion to be drawn as to which method provides the least deflection while being cost effective.

### 3.6.3. Design Vehicle Information

The information presented within Table 3-4 outlines the design criteria used when developing the issued for construction pavement design.

*Table 3-4: Mine Site B Relevant Design Vehicle Information*

| | **Cat 789 D**<br>(Caterpillar 2012) |
|---|---|
| **Engine** | Cat 3515C-HD |
| **Machine Weight** | 144.3 Tonne |
| **Nominal Payload Weight** | 181 Tonne |
| **Gross Machine Weight** | 324.3 Tonne |
| **Weight Distribution** | Front Axle – Empty 46%<br>Rear Axle – Empty 54%<br>Front Axle – Loaded 33%<br>Rear Axle – Loaded 67% |
| **Tyres** | 37.00 R 57 |
| **Tyre Diameter** | 3442mm |
| **Tyre Width** | 1072mm |

Figure 3-24 illustrates the typical Cat 789 vehicle dimensions.

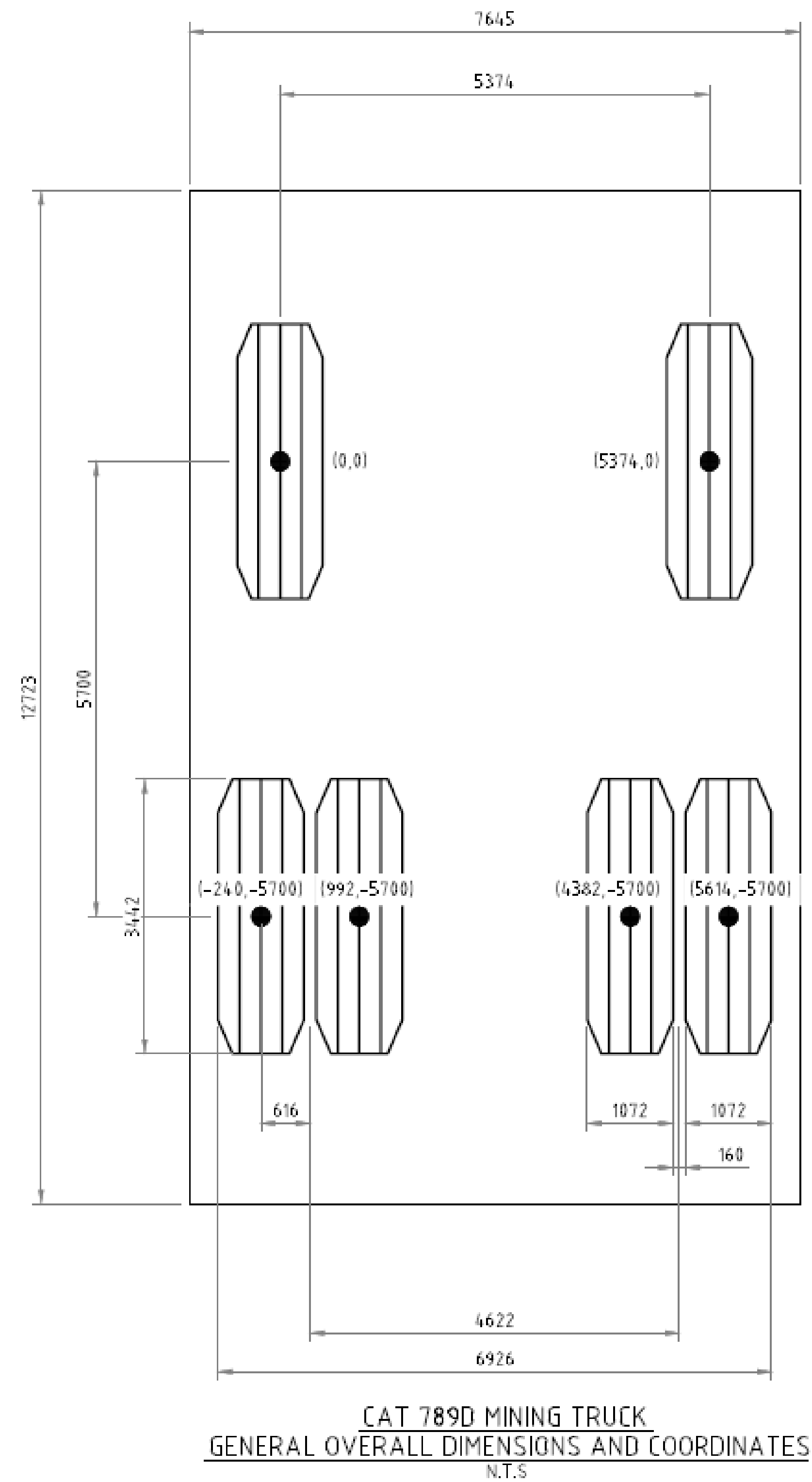



*Figure 3-24: CAT 789D Mining Truck General Overall Dimensions and Coordinates (Caterpillar 2012)*

### 3.6.4. Traffic Calculation

If the mine produces 10 million tonne of coal per annum they are processing approximately 14.3 million tonne of raw material. For the purpose of this *project*, it is assumed that the coal processing plant is located at one end of the mine. A Cat 789 is capable of carrying 181 tonne of material each load therefore annually there will be 79005 loads (216 / Day). Over the design life of the mine (assume 20 years) it is expected that the haul road design traffic will be 1,580,100 movements.

### 3.6.5. Subgrade Performance

Calculated the same as described in Section 3.5.6 the subgrade material constant and material damage exponent are:

- $k = 0.0031$ from Equation 2-12 and $b = 10.2685$ from Equation 2-13.

### 3.6.6. Case Study B Pavement Designs

Using the same calculations as described in section 3.5.7 unless noted otherwise. The following configurations were derived.

#### 3.6.6.1. Pavement Design B.1.1 – Kaufman and Ault Cover to Subgrade Method

The as-constructed design was designed and constructed some 20 years ago, it is assumed that Kaufman and Aults Cover to Subgrade method was used. Due to the wheel loads of the Cat 789, Thompsons Chart that replicates Kaufman and Aults Cover to Subgrade was used to replicate the design pavement configuration.

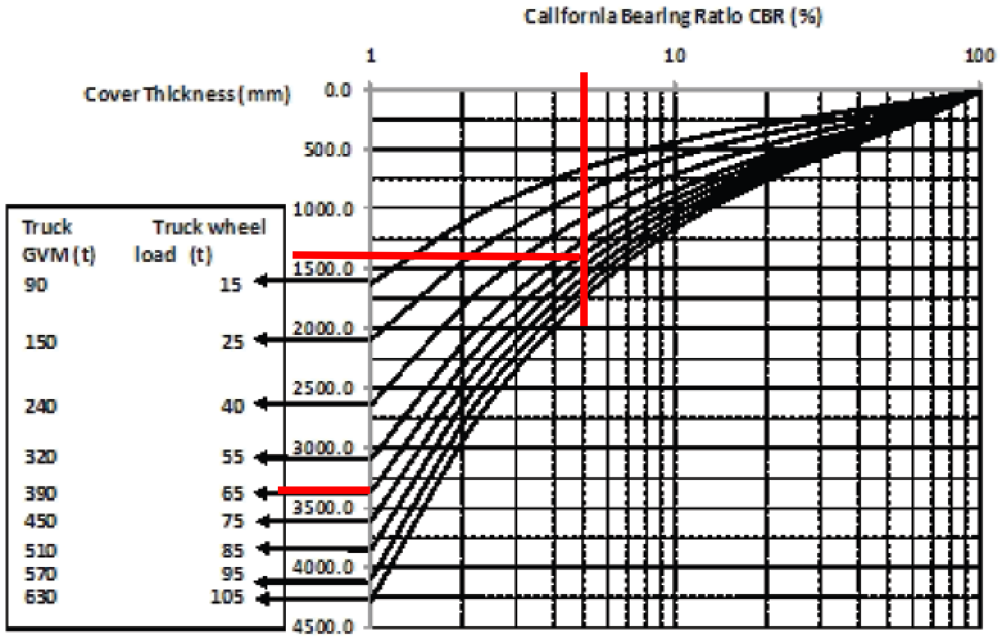



*Figure 3-25: Thompson's CBR Cover-Curve Design Chart – Pavement Design A.1.2*

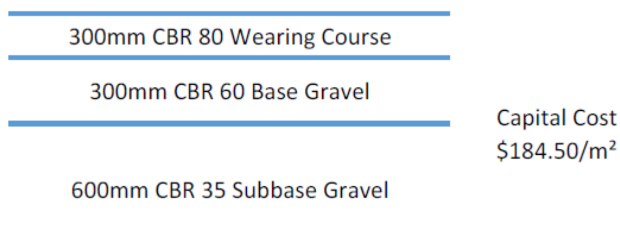



*Figure 3-26: Mine Site B – Pavement Design Configuration Option B.1.1*

#### 3.6.6.2. Pavement Design B.1.2 – Ahlvins Method

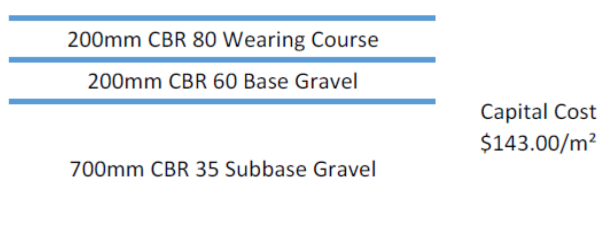



*Figure 3-27: Mine Site B – Pavement Design Configuration Option B.1.2*

### 3.6.6.3. Pavement Design B.1.3 – Ahlvins Method (Austroads Sublayering)

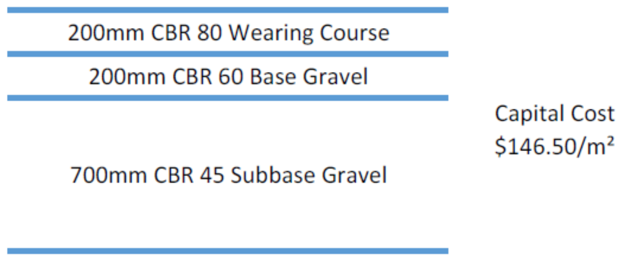



*Figure 3-28: Mine Site B – Pavement Design Configuration Option B.1.3*

### 3.6.6.4. Pavement Design B.1.4 – Thompsons Formula

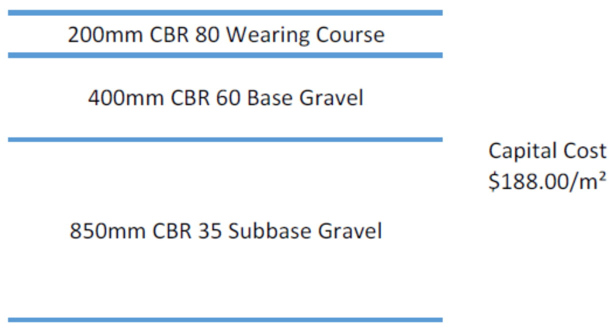



*Figure 3-29: Mine Site B – Pavement Design Configuration Option B.1.4*

### 3.6.6.5. Pavement Design B.1.5 – Thompsons Blast Rock Method

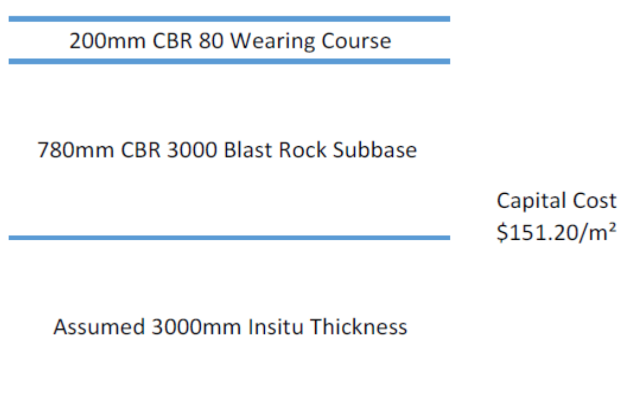



*Figure 3-30: Mine Site B – Pavement Design Configuration Option B.1.5*

#### 3.6.6.6. Pavement Design B.1.6 – Cement Modified Base Materials

| | |
|---|---|
| 200mm 2% Cement Modified Type 2.1 Wearing Course | Capital Cost $185.00/m² |
| 200mm 2% Cement Modified Type 2.2 Base Gravel | |
| 700mm CBR 80 Upper Subbase Gravel | |

*Figure 3-31: Mine Site B – Pavement Design Configuration Option B.1.6*

#### 3.6.6.7. Pavement Design B.1.7 – Ahlvins Method (Austroads Sublayering) with Improved Subbase

| | |
|---|---|
| 200mm CBR 80 Wearing Course | Capital Cost $140.50/m² |
| 200mm CBR 60 Base Gravel | |
| 300mm CBR 45 Upper Subbase Gravel | |
| 400mm CBR 15 Lime Stabilised Subgrade | |

*Figure 3-32: Mine Site B – Pavement Design Configuration Option B.1.7*

#### 3.6.7. Case Study B Maximum Deflection

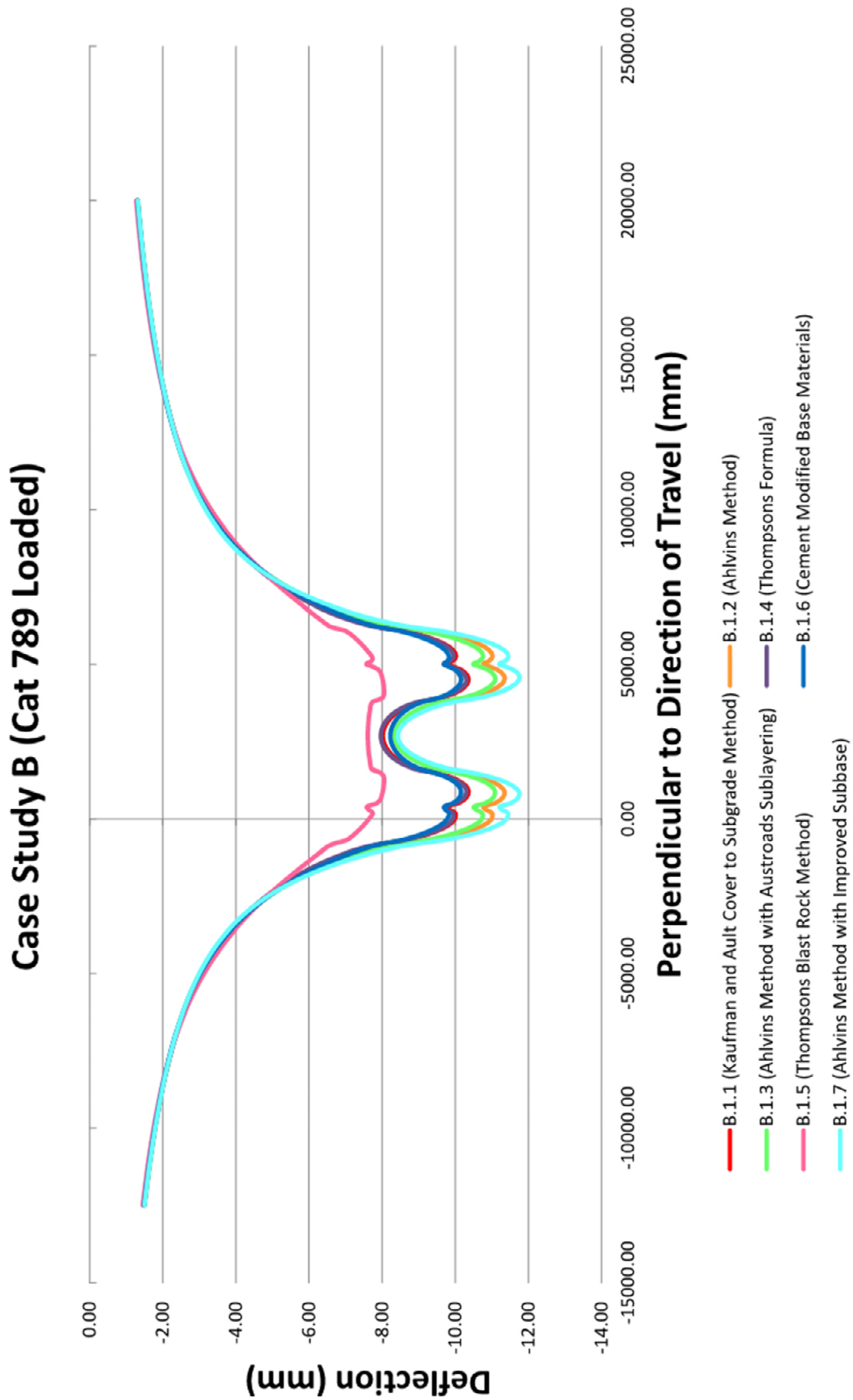



*Figure 3-33: Case Study B.1 Deflection Graph*

*Table 3-5: Case Study B Maximum Deflection Values*

| Pavement Design Option | Total Configuration Thickness | Capital Cost ($/m2) | Maximum Deflection |
|---|---|---|---|
| | **Case Study B Option B.1** | | |
| B.1.1 | 1400 | $184.50 | 10.00 |
| B.1.2 | 1100 | $143.00 | 11.34 |
| B.1.3 | 1100 | $146.50 | 11.08 |
| B.1.4 | 1450 | $188.00 | 10.30 |
| B.1.5 | 980 | $151.20 | 8.05 |
| B.1.6 | 1100 | $185.00 | 10.15 |
| B.1.7 | 1100 | $140.50 | 11.75 |

# CHAPTER 4

# 4. DISSCUSSION OF RESULTS

Overall twenty different pavement configurations were designed using different empirical methods and run through CIRCLY to determine their overall predicted deflection. Due to the nature of the loads being applied (in excess of 300 tonne) the deflections are expected to be quite large.

## 4.1. Case Study A.1

In order to eliminate some of the scenarios analysed within Chapter 3 the cost and deflection data was plotted to determine if there were any obvious outlies that could be disregarded. See Figure 4-1 below.

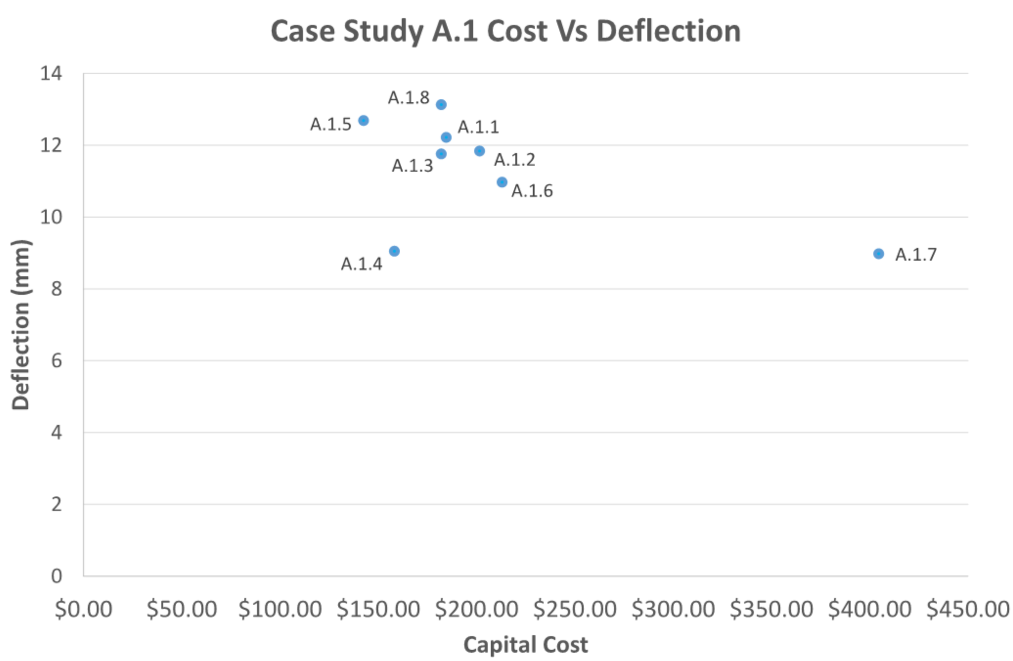



*Figure 4-1: Case Study A.1 Cost Vs Deflection*

Option A.1.7 produced the least deflection at 8.98mm, however this option had a total thickness of 3.0m. Such a thickness results in a capital cost of $404.59/m$^2$. This is not cost effective for any mining operation and will be disregarded.

Option A.1.4 was also considered an outlier; it had an overall deflection of 9.05mm. This was Thompsons Blast Rock Method. Even though the capital cost to construct this method is one of the cheapest ($158.20/m$^2$), using 3000MPa rock has its limitations.

Thompson's blast rock method utilises a blasted waste rock base layer with a typical modulus of 1500-3000MPa. This value is derived from consideration of a cement stabilized layer in its pre-cracked state. When compaction is poor, or layer thickness excessive he suggest that this value should be reduced to 1500-2000MPa (Thompson 2011b).

As a crushed rock it can only be considered as a cracked cement treated material because it would be difficult for it to develop a horizontal tensile capacity at the bottom of the layer. Austroads suggests that in a post cracking stage a cemented material should be modelled as a cross-anisotripic material with vertical modulus of 500MPa and a Poisson's ratio of 0.35 (Jameson 2012).

Therefore a considerable amount of testing would need to be undertaken to verify the modulus of any blast rock material. Typically any rock excavated within a quarry in Queensland is processed to produce a CBR 80 (Modulus 350MPa) suitable for pavement construction to Queensland TMR standards. This is a significantly different moduli to Thompsons suggested 1500-3000MPa.

Also the mines that have been considered are located within Central Queensland and produce Coal. Generally there is no blast rock available that is suitable for a road pavement and rock would need to be imported.

After disregarding these options the remaining 6 scenarios were plotted.

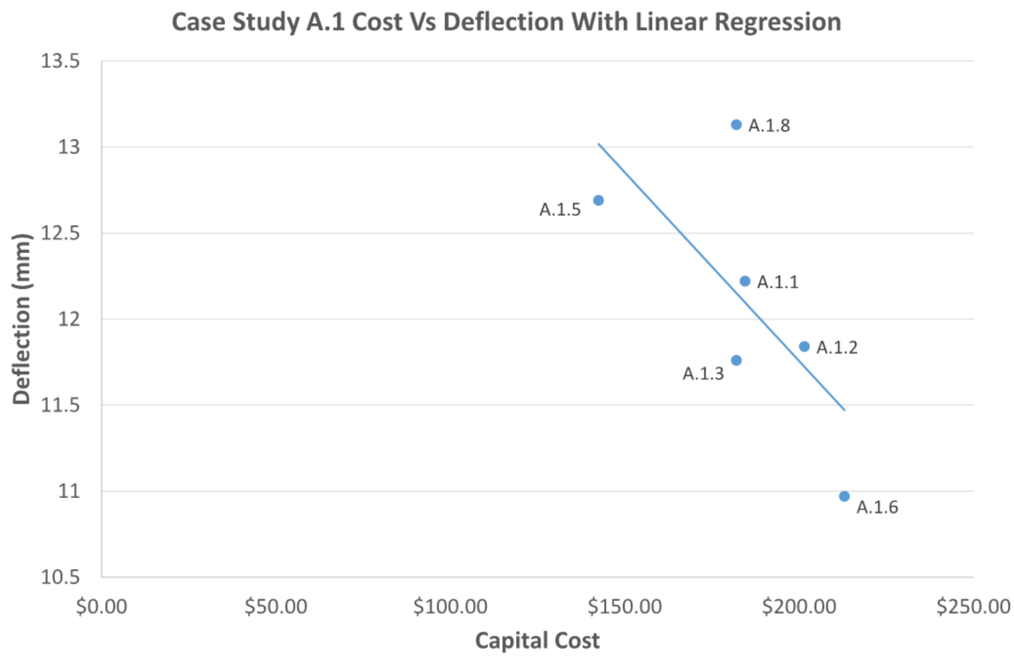



*Figure 4-2: Case Study A.1 Cost Vs Deflection with Linear Regression*

Determining the linear regression for Case Study A.1 allowed another three other scenarios to be disregarded. A.1.1, A.1.2 and A.1.8 are considered to have either too much deflection or are too expensive to construct.

This left three possible scenarios that will be discussed further:

Ahlvin's method of design coupled with Austroads Sublayering (Option A.1.3) which resulted in 11.76mm of deflection and a capital cost of $182.00/m$^2$.

Cement modifying the base and subbase (Option A.1.6) resulted in a deflection of 10.97mm and capital cost of $213.00/m$^2$.

Improving the subgrade by lime stabilisation is also an option, this would result in a deflection of 10.97mm and capital cost of $142.50/m$^2$.

## 4.2. Case Study A.2

Undertaking a similar analysis as described above allowed A.2.1 and A.2.2 to be disregarded as shown in Figure 4-3.

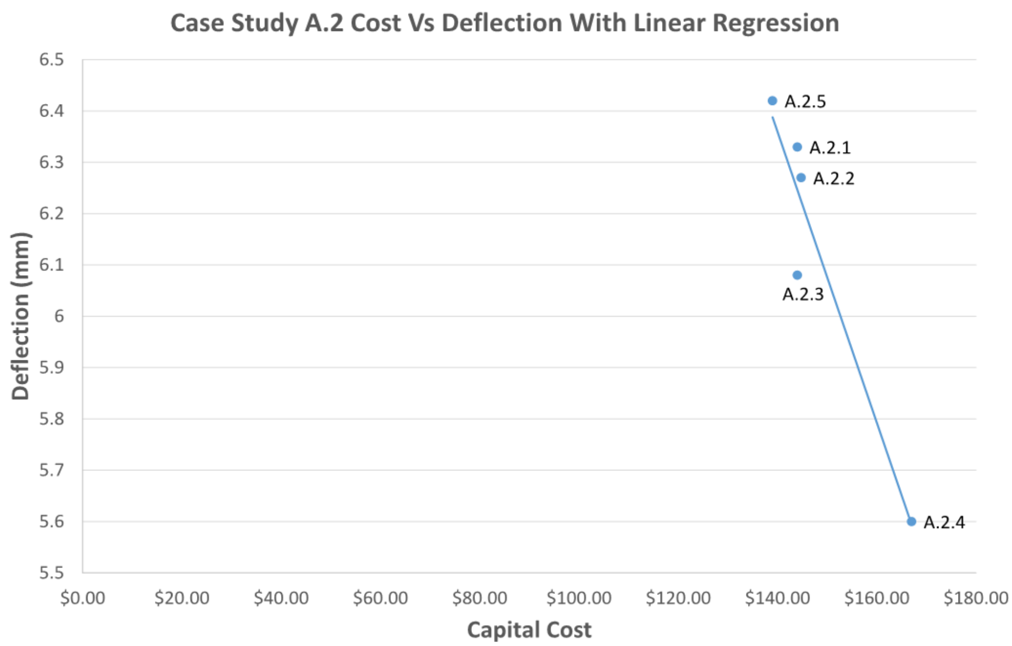



*Figure 4-3: Case Study A.2 Cost Vs Deflection With Linear Regression*

This left two distinct methods under the line, A.2.3 Ahlvin Method with Austroads Sublayering and A.2.4, Ahlvin Method (Austroads Sublayering) with Improved Subbase. Option A.2.5, cement treated base materials in this scenario is marginal however will be considered due to it being the cheapest pavement configuration to construct.

Case Study A.2.3 produced a deflection of 6.08mm and costs \$144.00m$^2$, pavement design option A.2.4 had a deflection of 5.60mm and costs \$167.00m$^2$ to construct and similarity A.2.4 produced a deflection of 6.42mm and will cost \$139.00m$^2$ to construct.

## 4.3. Case Study B.1

Plotting Case Study B scenarios cost verse deflection allowed Option B.1.5 to be disregarded due to it being a significant outlier as illustrated in Figure 4-4.

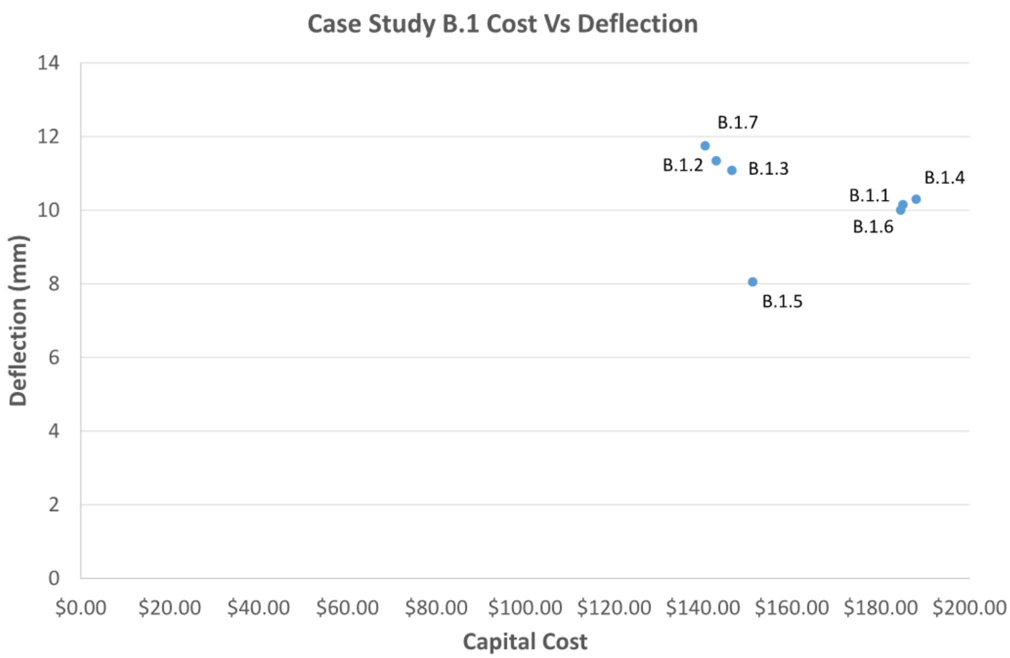



*Figure 4-4: Case Study B.1 Cost Vs Deflection*

This left 6 options, two which are above the line (Option B.1.4 and B.1.7) that will be disregarded.

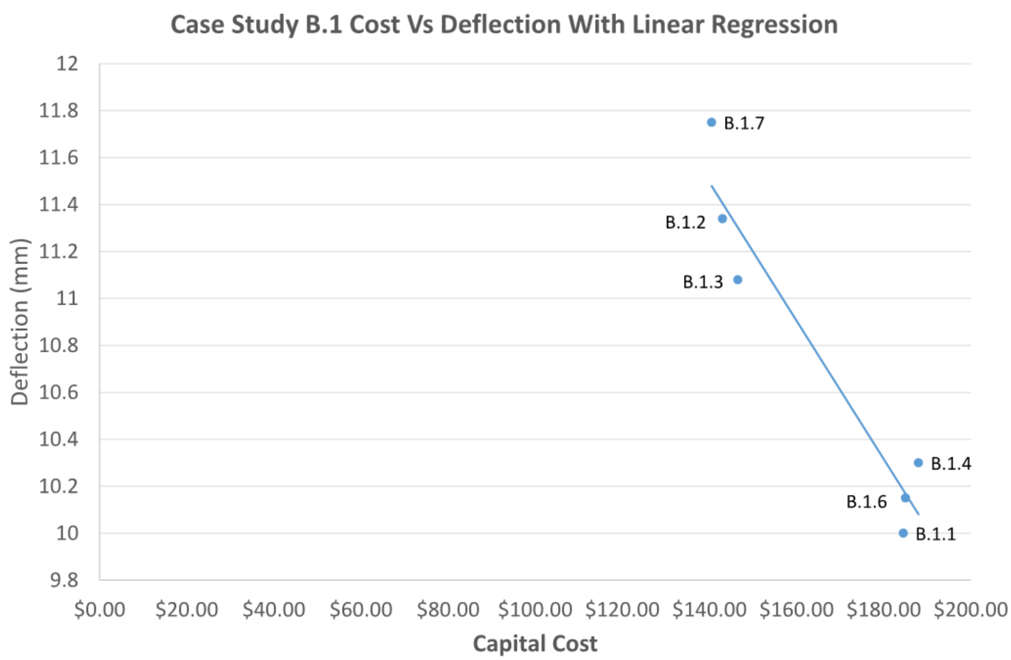



*Figure 4-5: Case Study B.1 Cost Vs Deflection with Linear Regression*

Option B.1.1, Kaufman and Aults method produced a deflection of 10mm and cost \$184.50/m$^2$ to construct, Option B.1.2, Ahlvin Method costing \$143.00/m$^2$ produced a 11.34mm deflection, Option B.1.3, Ahlvin Method with Austroads Sublayering produced 11.08mm deflection and cost \$146.50/m$^2$ to construct and finally Option B.1.6, cement modified subbase material produced a deflection of 10.15mm and cost \$185.00/m$^2$ to construct.

Overall Case Study B produced slightly different results to Case Study A however even with different loads a similar outcome has been observed.

## 4.4. Cumulative Damage Factor

CDF as described in Section 2.1.7 is a method of determining when a pavement is predicted to 'fail' for semi-empirical methods of pavement design. CDF takes into consideration the design repetitions of each vehicle, load combinations and the material performance properties. If CDF is greater than one the pavement has 'failed'. The pavement design methods that have been used throughout this project are primarily empirical methods. The overall pavement thickness and configurations have been determined using charts or formulas as described within Chapter 3. These configurations have been run through CIRCLY to calculate the overall deflection.

The CDF has been tabulated for discussion purposes only and is not a true representation of haul road pavements failure rate.

Table 4-1 below shows what the CDF is for each pavement option, and how many movements are actually possible if the CDF was 1.

*Table 4-1: Tabulated Number of Movements that Equals a CDF of 1*

| Tabulated Number of Movements That Equals CDF 1 | | | | |
|---|---|---|---|---|
| **Pavement Design Option** | **Traffic Calculation: Predicted Movements** | **CDF for Predicted Movements** | **Actual Movements to get as close to CDF 1 as possible** | **Actual CDF** |
| OP A.1.1 | 657000 | 64300 | 10 | 0.97 |
| OP A.1.2 | 657000 | 19100 | 35 | 1.02 |
| OP A.1.3 | 657000 | 27400 | 25 | 1.04 |
| OP A.1.4 | 657000 | 37 | 18000 | 1.01 |
| OP A.1.5 | 657000 | 200000 | 3.5 | 1.07 |
| OP A.1.6 | 657000 | 9010 | 75 | 1.03 |
| OP A.1.7 | 657000 | 1 | | |
| OP A.1.8 | 657000 | 522000 | 1.5 | 1.19 |
| OP A.2.1 | 657000 | 621 | 1100 | 1.04 |
| OP A.2.2 | 657000 | 558 | 1200 | 1.02 |
| OP A.2.3 | 657000 | 269 | 2500 | 1.02 |
| OP A.2.4 | 657000 | 83 | 8000 | 1.01 |
| OP A.2.5 | 657000 | 713 | 900 | 0.98 |
| Op A.3.1 | 657000 | 6050000000 | 0.0001 | 1.00 |
| OP B.1.1 | 1580100 | 40900 | 40 | 1.03 |
| OP B.1.2 | 1580100 | 889000 | 2 | 1.12 |
| OP B.1.3 | 1580100 | 558000 | 3 | 1.06 |
| OP B.1.4 | 1580100 | 27600 | 60 | 1.05 |
| OP B.1.5 | 1580100 | 70 | 22500 | 0.99 |
| OP B.1.6 | 1580100 | 101000 | 17 | 1.09 |
| OP B.1.7 | 1580100 | 1870000 | 0.9 | 1.07 |

For all of the pavements except option A.1.7 the CDF is greater than one. Section 2.1.7.1 above describes the development of CDF for use within CIRCLY. The failure criteria used was developed for the design methods that are used in HiPAVE (Wardle 2007). It was the only available criteria that related to heave duty pavements to use in CIRCLY, but clearly it is an inappropriate failure criteria to use in association with these other design methods.

## 4.5. Discussion

It is difficult to say which pavement design method will perform the best over time. The only real way to determine which design method is 'best' is to calculate and combine the capital and operating cost.

Typically there is a sum of money allocated by a stakeholder to construct a haul road. This sum of money is independent of maintenance and operations. A desired outcome would be to demonstrate the increase in maintenance and machinery costs due to constructing a poorly designed haul road.

In order to calculate the operating costs that are directly related to pavement design there needs to be a link. Rolling resistance is an obvious choice as rolling resistance is directly proportional to deflection.

In order to calculate the rolling resistance of each pavement design stresses and strains are required to produce a stress bulb. In reality this stress bulb cannot be symmetrical. When the pavement is in a deflected shape as the tyre is rotating it is 'pushing' a certain amount of the pavement effectively rolling up hill. There is also another force from the elastic part of the pavement that is rebounding and effectively helping the tyre along. For an example refer Figure 2-14. Due to the calculated stress bowl from CIRCLY not being symmetrical the only way to calculate the actual stresses and strains is by undertaking practical testing.

Future work is required to draw such a conclusion, without an analytical way of relating rolling resistance to deflection the increase in fuel consumption or wear and tear on the tyres cannot be calculated.

An observation that will also affect deflection and performance is how far the deflection curves extend past the edge of the trucks. For example the Cat 793 deflection bowl extends further than 10m past the edge of the truck. This would indicate that when two trucks are passing on a haul road their deflection bowls would combine and increase both maximum deflections.

## 4.6.Further Work

Ultimately a link between deflection and rolling resistance is required to determine the change in operating costs. In order to achieve this below are some of the recommended steps:

- Undertake Benkelman beam testing on multiple pavement configurations to determine if the deflections reported by CIRCLY are accurate.
- Determine a suitable method to calculate dynamic deflection for heavy mining equipment.
- Undertake test pavement sections on a haul road recording costs and maintenance regularity.
- Aim to establish a relationship between rolling resistance and deflection.

# CHAPTER 5

# 5. CONCLUSION

Overall without considering Thompsons Blast Rock method, it would be suggested that either Ahlvins Formula with Austroads Sublayering, Ahlvin's Method with Austroad Sublayering and improved subgrade, or cement modifying the base materials will produce the best performance when designing mine haul road pavements. These methods produce an adequate design while being comparatively costs effective. The costs are directly related to the overall deflection achieved.

However it should be noted that none of the methods used achieve a deflection of Thompsons suggested 3mm (Thompson 2011b) or Tannant and Regensburgs 6-8mm (Tannant & Regensburg 2001). Therefore irrespective of the method used the rolling resistance will always be more than desired.

The other foreseeable issue with specifying either of these methods as the preferred is neither the BMA nor the Rio Tinto's (two of Australia's largest mining operators) design manuals recognise them. Should further testing be undertaken to justify which method produces the least deflection and hence rolling resistance, an effort should be made to distribute it to the relevant engineers to inform them about the different publications available and how they could potentially save costs.

Such results will not be considered if costing is not undertaken to determine why spending a little more initially will help their maintenance plan in the long run. While current studies that give a link between rolling resistance and fuel consumption do not incorporate haul roads and their heavy vehicles and cannot be extrapolated literally. It is suggested that there is a 4:1 ratio between rolling resistance and fuel consumption when driving at a steady speed (Jamieson & Cenek 2004). Therefore there is a potential for substantial savings in mining operations to reduce their capital and operational costs.

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# Appendix A Project Specification

**University of Southern Queensland**

**FACULTY OF ENGINEERING AND SURVEYORING**

**ENG4111 & ENG4112 Research Project**

**PROJECT SPECIFICATION**

**FOR:** Anita STRACK

**TOPIC:** A Review of Australian Mine Haul Road Design & Maintenance Procedures

**SUPERVISORS:** USQ: Andreas Nataatmadja
Industry: Peter Foley

**ENROLMENT:** ENG4111 – Semester 1, 2015 & ENG4112 – Semester 2, 2015

**PROJECT AIM:** This project seeks to deliver a comparison between current practice and theoretical procedures to determine how this affects the cost and operations at certain mines within Queensland.

**CONFIDENTIALITY:** Due to confidentially agreements with mines it is possible location specific information may not be disclosed.

**PROGRAMME:** Revision B, August 12, 2015

1. Research theoretical practices for Australian Haul Road Design, including:
   a. Geometric Design
   b. Structural Design (Pavement)
   c. Functional Design and
   d. Maintenance
2. Establish relationships with site personal and obtain Site Specific information (Aim for 3 sites across Queensland) on their current Haul Road design and construction practices.
3. Collect and assemble data on selected case studies.
4. If geotechnical data is available undertake some theoretical pavement designs using CIRCLY (**CIRC**ular Loads **L**a**Y**er Systems) software for the chosen sites.
5. Critically compare theoretical design and actual practice of structural design.
6. Aim to demonstrate the additional deflection generated by the design vehicles using different pavement design methods.
7. Write a dissertation on the project in the required format.

**Agreed**

_______________(A.Strack) _______________(A.Nataatmadja) _______________(P.Foley)

Date: 12/8/2015 Date: 17/8/2015 Date: 12/8/2015

# Appendix B Example Onsite Evaluation of Wearing Course Functionality and Rolling Resistance

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

This is based on rating the wearing course on a section of haul road according to;

- How much is affected (the 'extent') by the particular defect, on a scale of 1-5
- How bad is the particular defect (the 'degree'), on a scale of 1-5

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

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

University of Pretoria Depts Mining and Civil & Bio-systems Engineering

**MINE HAUL ROAD FUNCTIONAL AND ROLLING RESISTANCE EVALUATION**

University of Pretoria

| | | | |
|---|---|---|---|
| DATE | | EVALUATOR | |
| ROAD | | VEHICLE SPEED km/hr (V) | |
| CHAINAGE | | TRAFFIC kt/day | |

| **DEFECT** | **FUNCTIONALITY** | | |
|---|---|---|---|
| | DEGREE (1-5) | EXTENT (1-5) | DEFECT SCORE |
| Potholes | | | |
| *Corrugations* | | | 4* |
| Rutting | | | |
| *Loose material* | | | 5* |
| *Stoniness - fixed* | | | 7* |
| *Dustiness* | | | 3* |
| Stoniness - loose | | | |
| Cracks - longit | | | |
| Cracks - slip | | | |
| Cracks - croc | | | |
| *Skid resistance - wet* | | | 9* |
| *Skid resistance - dry* | | | 9* |
| **TOTAL FUNCTIONALITY SCORE** $\Sigma$(Defect degree x defect extent) | | | |

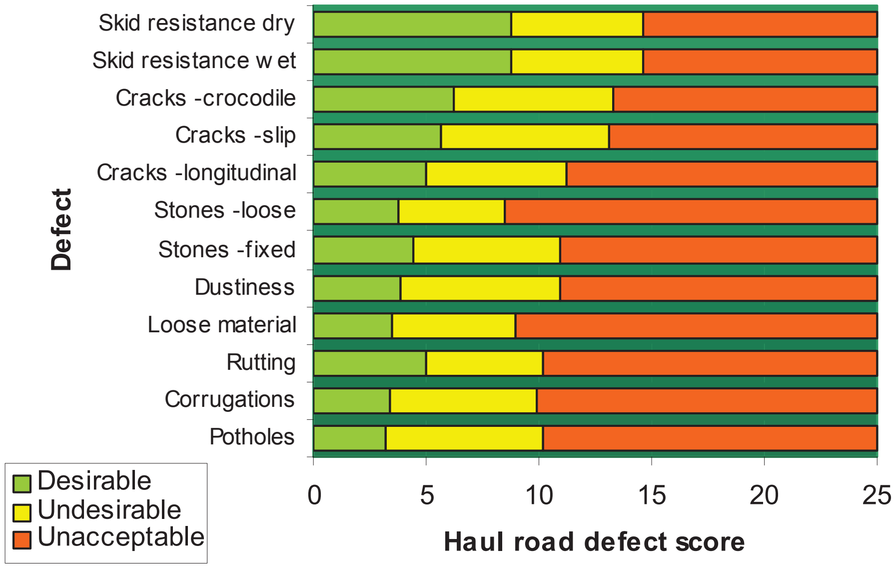
| **ROUGHNESS (Rolling resistance)** | | |
|---|---|---|
| DEGREE (1-5) | EXTENT (1-5) | DEFECT SCORE |
| | | |
| | | |
| | | |
| | | |
| | | |

| | |
|---|---|
| **TOTAL ROUGHNESS SCORE (RDS)** | |
| Refer to graph for rolling resistance percentages | |
| **ESTIMATED ROLLING RESISTANCE (%)** | |

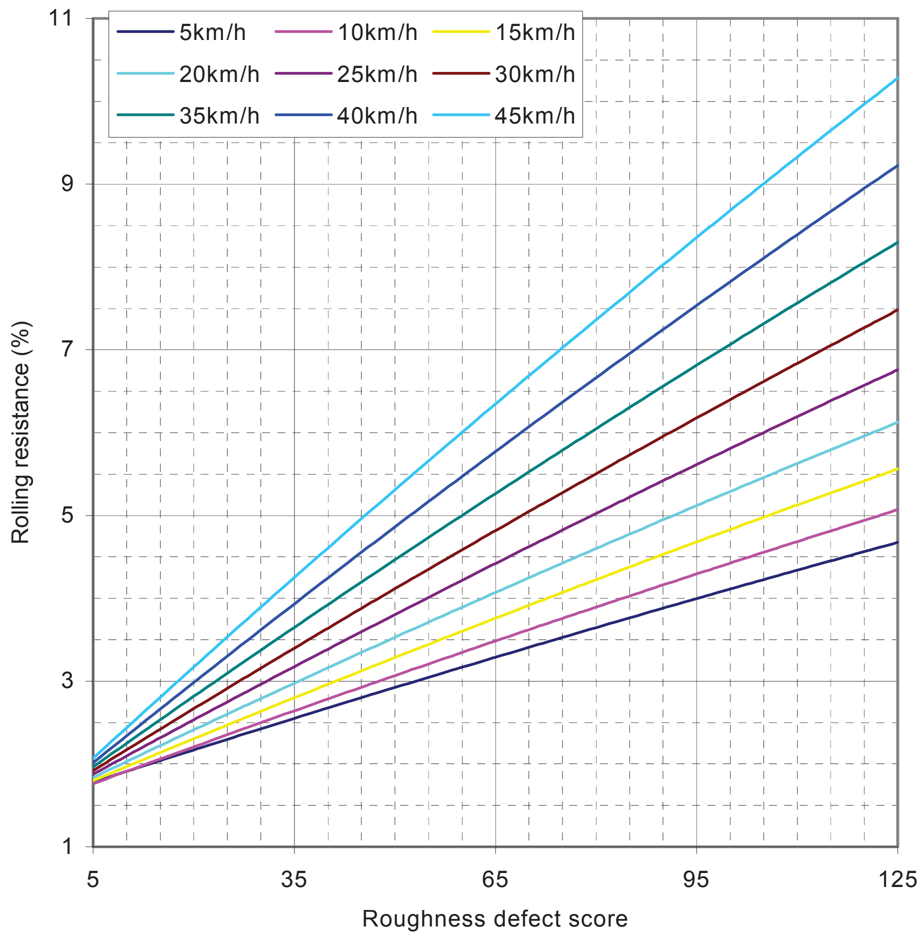
| Road maintenance recommended if any *critical* functional defect exceeds limit of acceptability (*) | Road maintenance imminent, but road trafficable | Road in good condition, no immediate maintenance needs |
|---|---|---|
| | | |

| **Comment** | | |
|---|---|---|
| **Drainage** | On road | |
| | Side of road | |
| **Erosion** | Longitudinal | |
| | Cross | |

**Functional performance acceptability criteria (example only – you may wish to use other defect score limits)**



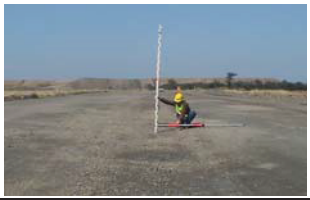
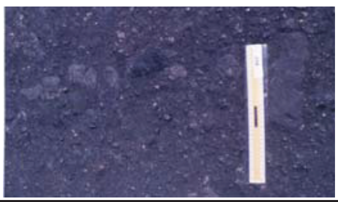

**Rolling resistance evaluation**



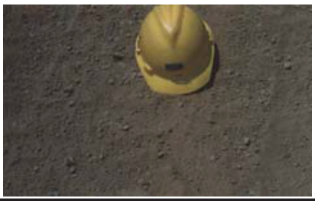
**General Description of Haul Road Extent Classification**

| EXTENT | DESCRIPTION (Percentage of haul road section length effected) |
|---|---|
| 1 | Isolated occurrence, less than 5% of road affected |
| 2 | Intermittent occurrence, between 5-15% of road affected. |
| 3 | Regular occurrence, between 16-30% of road affected. |
| 4 | Frequent occurrence, between 31-60% of road affected. |
| 5 | Extensive occurrence, more than 60% of the road affected. |

**General Description of Haul Road Degree Classification**

| CHARACTERISTIC | VISUAL DESCRIPTION | | |
|---|---|---|---|
| | Degree 1 | Degree 3 | Degree 5 |
| Potholes |  |  |  |
| Corrugations |  |  |  |
| Rutting |  |  |  |
| Loose material |  |  |  |
| Dustiness |  |  |  |
| Stoniness - fixed in wearing course |  |  |  |

## General Description of Haul Road Degree Classification

| CHARACTERISTIC | VISUAL DESCRIPTION | | |
|---|---|---|---|
| | Degree 1 | Degree 3 | Degree 5 |
| Cracks - longitudinal | None |  |  |
| Cracks - slip |  |  |  |
| Cracks - crocodile |  |  |  |
| Skid resistance - wet |  |  |  |
| Skid resistance - dry |  |  |  |
| Drainage on road |  |  |  |
| Drainage at roadside |  |  |  |

# Appendix C Sample Questionnaire

1. Who does the haul road design?
    a. Onsite
    b. In house designers offsite
    c. External consultant
2. What standards are used for geometric design?
3. What testing is done to determine pavement design parameters?
4. What method is used for pavement design?
    a. None
    b. Standardised site design
    c. Empirical design charts
    d. Mechanistic computer based design
5. What as-built data is collected?
6. Who manages the haul road network?
7. How is maintenance performed?
8. Are maintenance costs recorded?

# Appendix D Case Study A Questionnaire

1. *Who does the haul road design?*

a. Onsite

2. *What standards are used for geometric design?*

We generally refer to the Site Specific Surface Haul Road Design Manual

3. *What testing is done to determine pavement design parameters?*

We don’t do any testing

4. *What method is used for pavement design?*

a. None I’ll explain – on site we are constantly digging overburden, hauling and dumping in a spoil pile somewhere. The trucks are constantly running over a surface that has either just been blasted or just been dumped over. If we need to widen a haul road or make a modification we just strip the topsoil and sheet the road with a gravel wearing course. Wherever the trucks run they are heavy enough to compact material underneath. There are some other issues that we do pay attention to like water (culverts), or other geotechnical constraints (faults, mud at the bottom of spoil piles that causes failure etc).

5. *What as-built data is collected?*

In terms of pavement design – none. Otherwise we take weekly and monthly aerial surveys of road and pits.

6. *Who manages the haul road network?*

We have a dedicated road crew (24M grader, D10 dozer, 2 x scrapers, reject haul truck, water cart and a contractor on site with (2 x 35t excavators, 16M grader, water cart)

7. *How is maintenance performed?*

Combination of ad-hoc and planned. If parts of the road network need to graded or watered, an operator will call the supervisor and equipment sent down. We also schedule all our stripping and coal mining 3 months in advance. So we know when we are going to mine a certain seam, or strip overburden in an area the road crew need to go in and prepare the road before hand. They will go in with a dozer and push material, then grade, and then finally sheet with coal reject as a wearing course.

8. *How is maintenance performed?*

Yes – road crew only look after road maintenance and all operating costs are recorded.

# Appendix E Case Study B Questionnaire

1. *Who does the haul road design?*

An external consultant designed and built the haul road. From there the roads were generally maintained using material won onsite, therefore designed / made up onsite or the original design drawings referenced.

2. *What standards are used for geometric design?*

I never actually saw a standard for this mine.

3. *What testing is done to determine pavement design parameters?*

I'd say initially (to complete the haul road design for a new mine), but not ongoing.

4. *What method is used for pavement design?*

Unsure

5. *What as-built data is collected?*

Originally I'd say yes (ie: when the mine was built), but unlikely that it was collected ongoing (when maintenance was completed).

6. *Who manages the haul road network?*

The OCE. Open Cut Examiner

7. *How is maintenance performed?*

As directed by the OCE(s). Some mines have graders & water carts doing maintenance almost full time.

8. *Are maintenance costs recorded?*

Unsure. Mines may record them using a separate booking / work break down code for maintenance.

9. *What Haul Trucks do they use?*

What is available onsite – 789's.

# Appendix F Case Study A CIRCLY Model Output Information

CIRCLY Version 5.0u (8 April 2013)

Job Title: A.1.1

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: Cat 793 Title: Cat 793

| Load No. | Load ID | Movements |
|---|---|---|
| 1 | Cat 793 | 6.57E+05 |

Details of Load Groups:

| Load No. | Load ID | Load Category | Load Type | Radius | Pressure/ Ref. stress | Exponent |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | Cat 793 | Vertical Force | 590.0 | 0.70 | 0.00 |

Load Locations:

| Location No. | Load ID | Gear No. | X | Y | Scaling Factor | Theta |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | 1 | 0.0 | 0.0 | 1.00E+00 | 0.00 |
| 2 | Cat 793 | 2 | -423.0 | -5905.0 | 1.00E+00 | 0.00 |
| 3 | Cat 793 | 2 | 1091.0 | -5905.0 | 1.00E+00 | 0.00 |
| 4 | Cat 793 | 1 | 5630.0 | 0.0 | 1.00E+00 | 0.00 |
| 5 | Cat 793 | 2 | 4539.0 | -5905.0 | 1.00E+00 | 0.00 |
| 6 | Cat 793 | 2 | 6053.0 | -5905.0 | 1.00E+00 | 0.00 |

Layout of result points on horizontal plane:
Xmin: -12500 Xmax: 20000 Xdel: 100
Y: 0

Details of Layered System:

ID: A.1.1 Title: Case Study A.1.1

| Layer No. | Lower i/face | Material ID | Isotropy | Modulus (or Ev) | P.Ratio (or vvh) | F | Eh | vh |
|---|---|---|---|---|---|---|---|---|
| 1 | rough | Iso E350 | Iso. | 3.50E+02 | 0.35 | | | |
| 2 | rough | Iso E350 | Iso. | 3.50E+02 | 0.35 | | | |
| 3 | rough | Iso E240 | Iso. | 2.40E+02 | 0.35 | | | |
| 4 | rough | Iso E120 | Iso. | 1.20E+02 | 0.35 | | | |
| 5 | rough | Sub_CBR5 H | Aniso. | 5.00E+01 | 0.45 | 3.45E+01 | 2.50E+01 | 0.45 |

Performance Relationships:

| Layer No. | Location | Performance ID | Component | Perform. Constant | Perform. Exponent | Traffic Multiplier |
|---|---|---|---|---|---|---|
| 5 | top | Sub 5 Per | EZZ | 0.003100 | 10.269 | 1.000 |

Reliability Factors: Not Used.

Results:

| Layer | Thickness | Material | Load | Critical | CDF |
|---|---|---|---|---|---|

| No. | | ID | ID | Strain | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 300.00 | Iso E350 | | n/a | n/a |
| 3 | 300.00 | Iso E240 | | n/a | n/a |
| 4 | 600.00 | Iso E120 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 793 | 2.31E-03 | 6.43E+04 |

CIRCLY Version 5.0u (8 April 2013)

Job Title: A.1.2

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: Cat 793 Title: Cat 793

| Load No. | Load ID | Movements |
|---|---|---|
| 1 | Cat 793 | 6.57E+05 |

Details of Load Groups:

| Load No. | Load ID | Load Category | Load Type | Radius | Pressure/ Ref. stress | Exponent |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | Cat 793 | Vertical Force | 590.0 | 0.70 | 0.00 |

Load Locations:

| Location No. | Load ID | Gear No. | X | Y | Scaling Factor | Theta |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | 1 | 0.0 | 0.0 | 1.00E+00 | 0.00 |
| 2 | Cat 793 | 2 | -423.0 | -5905.0 | 1.00E+00 | 0.00 |
| 3 | Cat 793 | 2 | 1091.0 | -5905.0 | 1.00E+00 | 0.00 |
| 4 | Cat 793 | 1 | 5630.0 | 0.0 | 1.00E+00 | 0.00 |
| 5 | Cat 793 | 2 | 4539.0 | -5905.0 | 1.00E+00 | 0.00 |
| 6 | Cat 793 | 2 | 6053.0 | -5905.0 | 1.00E+00 | 0.00 |

Layout of result points on horizontal plane:
Xmin: -1000 Xmax: 1000 Xdel: 100
Y: 0

Details of Layered System:

ID: A.1.2 Title: Case Study A.1.2

| Layer No. | Lower i/face | Material ID | Isotropy | Modulus (or Ev) | P.Ratio (or vvh) | F | Eh | vh |
|---|---|---|---|---|---|---|---|---|
| 1 | rough | Iso E350 | Iso. | 3.50E+02 | 0.35 | | | |
| 2 | rough | Iso E350 | Iso. | 3.50E+02 | 0.35 | | | |
| 3 | rough | Iso E240 | Iso. | 2.40E+02 | 0.35 | | | |
| 4 | rough | Iso E120 | Iso. | 1.20E+02 | 0.35 | | | |
| 5 | rough | Sub_CBR5 H | Aniso. | 5.00E+01 | 0.45 | 3.45E+01 | 2.50E+01 | 0.45 |

Performance Relationships:

| Layer No. | Location | Performance ID | Component | Perform. Constant | Perform. Exponent | Traffic Multiplier |
|---|---|---|---|---|---|---|
| 5 | top | Sub 5 Per | EZZ | 0.003100 | 10.269 | 1.000 |

Reliability Factors: Not Used.

Results:

Layer Thickness Material Load Critical CDF

| No. | | ID | ID | Strain | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 300.00 | Iso E350 | | n/a | n/a |
| 3 | 400.00 | Iso E240 | | n/a | n/a |
| 4 | 650.00 | Iso E120 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 793 | 2.05E-03 | 1.91E+04 |

```
CIRCLY Version 5.0u (8 April 2013)

Job Title: A.1.3

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 793 Title: Cat 793

   Load   Load          Movements
    No.   ID
    1     Cat 793       6.57E+05

Details of Load Groups:

   Load   Load        Load        Load             Radius    Pressure/
Exponent
    No.   ID          Category    Type                       Ref. stress
    1     Cat 793     Cat 793     Vertical Force    590.0     0.70
0.00

   Load Locations:
   Location   Load         Gear           X          Y      Scaling     Theta
    No.       ID           No.                              Factor
    1         Cat 793       1             0.0        0.0    1.00E+00
0.00
    2         Cat 793       2          -423.0    -5905.0    1.00E+00
0.00
    3         Cat 793       2          1091.0    -5905.0    1.00E+00
0.00
    4         Cat 793       1          5630.0        0.0    1.00E+00
0.00
    5         Cat 793       2          4539.0    -5905.0    1.00E+00
0.00
    6         Cat 793       2          6053.0    -5905.0    1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -1000   Xmax:  1000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: A.1.6 Title: Case Study A.1.3

   Layer  Lower    Material     Isotropy    Modulus     P.Ratio

    No.   i/face   ID                       (or Ev)     (or vvh)  F
Eh         vh
    1     rough    Iso E350     Iso.        3.50E+02    0.35
    2     rough    Iso E290     Iso.        2.90E+02    0.35
    3     rough    Iso E240     Iso.        2.40E+02    0.35
    4     rough    Iso E206     Iso.        2.06E+02    0.35
    5     rough    Sub_CBR5 H   Aniso.      5.00E+01    0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component   Perform.    Perform.  Traffic
    No.            ID                       Constant    Exponent  Multiplier
    5     top      Sub 5 Per    EZZ          0.003100    10.269     1.000

   Reliability Factors: Not Used.


Results:

   Layer  Thickness  Material     Load         Critical       CDF
```

| No. | | ID | ID | Strain | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 300.00 | Iso E290 | | n/a | n/a |
| 3 | 300.00 | Iso E240 | | n/a | n/a |
| 4 | 600.00 | Iso E206 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 793 | 2.13E-03 | 2.74E+04 |

```
CIRCLY Version 5.0u (8 April 2013)

Job Title: A.1.4

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 793 Title: Cat 793

   Load   Load          Movements
    No.   ID
    1     Cat 793       6.57E+05

Details of Load Groups:

   Load   Load        Load        Load            Radius    Pressure/
Exponent
    No.   ID          Category    Type                      Ref. stress
    1     Cat 793     Cat 793     Vertical Force    590.0    0.70
0.00

   Load Locations:
   Location   Load        Gear          X          Y      Scaling     Theta
    No.       ID          No.                             Factor
    1         Cat 793      1             0.0        0.0   1.00E+00
0.00
    2         Cat 793      2          -423.0    -5905.0   1.00E+00
0.00
    3         Cat 793      2          1091.0    -5905.0   1.00E+00
0.00
    4         Cat 793      1          5630.0        0.0   1.00E+00
0.00
    5         Cat 793      2          4539.0    -5905.0   1.00E+00
0.00
    6         Cat 793      2          6053.0    -5905.0   1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: A.1.3 Title: Case Study A.1.4

   Layer  Lower    Material     Isotropy   Modulus    P.Ratio

    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Iso E350     Iso.       3.50E+02   0.35
    2     rough    Iso E3000    Iso.       3.00E+03   0.35
    3     rough    Sub_CBR5 H   Aniso.     5.00E+01   0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.            ID                      Constant   Exponent  Multiplier
    3     top      Sub 5 Per    EZZ         0.003100   10.269     1.000

   Reliability Factors: Not Used.


Results:

   Layer  Thickness  Material     Load          Critical       CDF
    No.              ID           ID            Strain
    1      200.00    Iso E350                    n/a           n/a
```

| | | | | | |
|---|---|---|---|---|---|
| 2 | 830.00 | Iso E3000 | | n/a | n/a |
| 3 | 0.00 | Sub_CBR5 H | Cat 793 | 1.12E-03 | 3.70E+01 |

CIRCLY Version 5.0u (8 April 2013)

Job Title: A.1.5

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: Cat 793 Title: Cat 793

| Load No. | Load ID | Movements |
|---|---|---|
| 1 | Cat 793 | 6.57E+05 |

Details of Load Groups:

| Load No. | Load ID | Load Category | Load Type | Radius | Pressure/ Ref. stress | Exponent |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | Cat 793 | Vertical Force | 590.0 | 0.70 | 0.00 |

Load Locations:

| Location No. | Load ID | Gear No. | X | Y | Scaling Factor | Theta |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | 1 | 0.0 | 0.0 | 1.00E+00 | 0.00 |
| 2 | Cat 793 | 2 | -423.0 | -5905.0 | 1.00E+00 | 0.00 |
| 3 | Cat 793 | 2 | 1091.0 | -5905.0 | 1.00E+00 | 0.00 |
| 4 | Cat 793 | 1 | 5630.0 | 0.0 | 1.00E+00 | 0.00 |
| 5 | Cat 793 | 2 | 4539.0 | -5905.0 | 1.00E+00 | 0.00 |
| 6 | Cat 793 | 2 | 6053.0 | -5905.0 | 1.00E+00 | 0.00 |

Layout of result points on horizontal plane:
Xmin: -12500   Xmax:  20000   Xdel:  100
Y:     0

Details of Layered System:

ID: A.1.5 Title: Case Study A.1.5

| Layer No. | Lower i/face | Material ID | Isotropy | Modulus (or Ev) | P.Ratio (or vvh) | F | Eh | vh |
|---|---|---|---|---|---|---|---|---|
| 1 | rough | Iso E350 | Iso. | 3.50E+02 | 0.35 | | | |
| 2 | rough | Iso E290 | Iso. | 2.90E+02 | 0.35 | | | |
| 3 | rough | Iso E240 | Iso. | 2.40E+02 | 0.35 | | | |
| 4 | rough | subsltE190 | Aniso. | 1.20E+02 | 0.45 | 8.30E+01 | 6.00E+01 | 0.45 |
| 5 | rough | Sub_CBR5 H | Aniso. | 5.00E+01 | 0.45 | 3.45E+01 | 2.50E+01 | 0.45 |

Performance Relationships:

| Layer No. | Location | Performance ID | Component | Perform. Constant | Perform. Exponent | Traffic Multiplier |
|---|---|---|---|---|---|---|
| 5 | top | Sub 5 Per | EZZ | 0.003100 | 10.269 | 1.000 |

Reliability Factors: Not Used.

Details of Layers to be sublayered:
Layer no.  4:  Austroads (2004) sublayering

Results:

| Layer No. | Thickness | Material ID | Load ID | Critical Strain | CDF |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 300.00 | Iso E290 | | n/a | n/a |
| 3 | 400.00 | Iso E240 | | n/a | n/a |
| 4 | 500.00 | subsltE190 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 793 | 2.58E-03 | 2.00E+05 |

CIRCLY Version 5.0u (8 April 2013)

Job Title: A.1.6

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: Cat 793 Title: Cat 793

| Load No. | Load ID | Movements |
|---|---|---|
| 1 | Cat 793 | 6.57E+05 |

Details of Load Groups:

| Load No. | Load ID | Load Category | Load Type | Radius | Pressure/ Ref. stress | Exponent |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | Cat 793 | Vertical Force | 590.0 | 0.70 | 0.00 |

Load Locations:

| Location No. | Load ID | Gear No. | X | Y | Scaling Factor | Theta |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | 1 | 0.0 | 0.0 | 1.00E+00 | 0.00 |
| 2 | Cat 793 | 2 | -423.0 | -5905.0 | 1.00E+00 | 0.00 |
| 3 | Cat 793 | 2 | 1091.0 | -5905.0 | 1.00E+00 | 0.00 |
| 4 | Cat 793 | 1 | 5630.0 | 0.0 | 1.00E+00 | 0.00 |
| 5 | Cat 793 | 2 | 4539.0 | -5905.0 | 1.00E+00 | 0.00 |
| 6 | Cat 793 | 2 | 6053.0 | -5905.0 | 1.00E+00 | 0.00 |

Layout of result points on horizontal plane:
Xmin: -12500 Xmax: 20000 Xdel: 100
Y: 0

Details of Layered System:

ID: A.1.6 Title: Case Study A.1.6

| Layer No. | Lower i/face | Material ID | Isotropy | Modulus (or Ev) | P.Ratio (or vvh) | F | Eh | vh |
|---|---|---|---|---|---|---|---|---|
| 1 | rough | Iso E500 | Iso. | 5.00E+02 | 0.35 | | | |
| 2 | rough | Iso E400 | Iso. | 4.00E+02 | 0.35 | | | |
| 3 | rough | Iso E350 | Iso. | 3.50E+02 | 0.35 | | | |
| 4 | rough | Iso E240 | Iso. | 2.40E+02 | 0.35 | | | |
| 5 | rough | Sub_CBR5 H | Aniso. | 5.00E+01 | 0.45 | 3.45E+01 | 2.50E+01 | 0.45 |

Performance Relationships:

| Layer No. | Location | Performance ID | Component | Perform. Constant | Perform. Exponent | Traffic Multiplier |
|---|---|---|---|---|---|---|
| 5 | top | Sub 5 Per | EZZ | 0.003100 | 10.269 | 1.000 |

Reliability Factors: Not Used.

Results:

Layer Thickness Material Load Critical CDF

| No. | | ID | ID | Strain | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E500 | | n/a | n/a |
| 2 | 300.00 | Iso E400 | | n/a | n/a |
| 3 | 300.00 | Iso E350 | | n/a | n/a |
| 4 | 600.00 | Iso E240 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 793 | 1.91E-03 | 9.01E+03 |

CIRCLY Version 5.0u (8 April 2013)

Layer no.  5 is INCLUDED in max. CDF calculation
Job Title: A.1.7

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: Cat 793 Title: Cat 793

| Load No. | Load ID | Movements |
|---|---|---|
| 1 | Cat 793 | 6.57E+05 |

Details of Load Groups:

| Load No. | Load ID | Load Category | Load Type | Radius | Pressure/ Ref. stress | Exponent |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | Cat 793 | Vertical Force | 590.0 | 0.70 | 0.00 |

Load Locations:

| Location No. | Load ID | Gear No. | X | Y | Scaling Factor | Theta |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | 1 | 0.0 | 0.0 | 1.00E+00 | 0.00 |
| 2 | Cat 793 | 2 | -423.0 | -5905.0 | 1.00E+00 | 0.00 |
| 3 | Cat 793 | 2 | 1091.0 | -5905.0 | 1.00E+00 | 0.00 |
| 4 | Cat 793 | 1 | 5630.0 | 0.0 | 1.00E+00 | 0.00 |
| 5 | Cat 793 | 2 | 4539.0 | -5905.0 | 1.00E+00 | 0.00 |
| 6 | Cat 793 | 2 | 6053.0 | -5905.0 | 1.00E+00 | 0.00 |

Layout of result points on horizontal plane:
Xmin: -12500   Xmax:  20000   Xdel:  100
Y:     0

Details of Layered System:

ID: A.1.7 Title: Case Study A.1.7

| Layer No. | Lower i/face | Material ID | Isotropy | Modulus (or Ev) | P.Ratio (or vvh) | F | Eh | vh |
|---|---|---|---|---|---|---|---|---|
| 1 | rough | Iso E350 | Iso. | 3.50E+02 | 0.35 | | | |
| 2 | rough | Iso E290 | Iso. | 2.90E+02 | 0.35 | | | |
| 3 | rough | Iso E240 | Iso. | 2.40E+02 | 0.35 | | | |
| 4 | rough | Iso E206 | Iso. | 2.06E+02 | 0.35 | | | |
| 5 | rough | Sub_CBR5 H | Aniso. | 5.00E+01 | 0.45 | 3.45E+01 | 2.50E+01 | 0.45 |

Performance Relationships:

| Layer No. | Location | Performance ID | Component | Perform. Constant | Perform. Exponent | Traffic Multiplier |
|---|---|---|---|---|---|---|
| 5 | top | Sub 5 Per | EZZ | 0.003100 | 10.269 | 1.000 |

Reliability Factors: Not Used.

Automatic layer thickness design:
Layer number to be designed:  2

Minimum thickness:  0
Maximum thickness:  5000

Results:

| Layer No. | Thickness | Material ID | Load ID | Critical Strain | CDF |
|---|---|---|---|---|---|
| 1 | 300.00 | Iso E350 | | n/a | n/a |
| 2 | 1793.98 | Iso E290 | | n/a | n/a |
| 3 | 300.00 | Iso E240 | | n/a | n/a |
| 4 | 600.00 | Iso E206 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 793 | 7.86E-04 | 9.98E-01 |

CIRCLY Version 5.0u (8 April 2013)

Job Title: A.1.8

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: Cat 793 Title: Cat 793

| Load No. | Load ID | Movements |
|---|---|---|
| 1 | Cat 793 | 6.57E+05 |

Details of Load Groups:

| Load No. | Load ID | Load Category | Load Type | Radius | Pressure/ Ref. stress | Exponent |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | Cat 793 | Vertical Force | 590.0 | 0.70 | 0.00 |

Load Locations:

| Location No. | Load ID | Gear No. | X | Y | Scaling Factor | Theta |
|---|---|---|---|---|---|---|
| 1 | Cat 793 | 1 | 0.0 | 0.0 | 1.00E+00 | 0.00 |
| 2 | Cat 793 | 2 | -423.0 | -5905.0 | 1.00E+00 | 0.00 |
| 3 | Cat 793 | 2 | 1091.0 | -5905.0 | 1.00E+00 | 0.00 |
| 4 | Cat 793 | 1 | 5630.0 | 0.0 | 1.00E+00 | 0.00 |
| 5 | Cat 793 | 2 | 4539.0 | -5905.0 | 1.00E+00 | 0.00 |
| 6 | Cat 793 | 2 | 6053.0 | -5905.0 | 1.00E+00 | 0.00 |

Layout of result points on horizontal plane:
Xmin: -12500 Xmax: 20000 Xdel: 100
Y: 0

Details of Layered System:

ID: A.1.8 Anis Title: Case Study A.1.8 Aniso

| Layer No. | Lower i/face | Material ID | Isotropy | Modulus (or Ev) | P.Ratio (or vvh) | F | Eh | vh |
|---|---|---|---|---|---|---|---|---|
| 1 | rough | Aniso 350 | Aniso. | 3.50E+02 | 0.35 | 2.59E+02 | 1.75E+02 | 0.35 |
| 2 | rough | Aniso 350 | Aniso. | 3.50E+02 | 0.35 | 2.59E+02 | 1.75E+02 | 0.35 |
| 3 | rough | Aniso 240 | Aniso. | 2.40E+02 | 0.35 | 1.78E+02 | 1.20E+02 | 0.35 |
| 4 | rough | Aniso 120 | Aniso. | 1.20E+02 | 0.35 | 8.90E+01 | 6.00E+01 | 0.35 |
| 5 | rough | Sub_CBR5 H | Aniso. | 5.00E+01 | 0.45 | 3.45E+01 | 2.50E+01 | 0.45 |

Performance Relationships:

| Layer No. | Location | Performance ID | Component | Perform. Constant | Perform. Exponent | Traffic Multiplier |
|---|---|---|---|---|---|---|
| 5 | top | Sub 5 Per | EZZ | 0.003100 | 10.269 | 1.000 |

Reliability Factors: Not Used.

Results:

| Layer No. | Thickness | Material ID | Load ID | Critical Strain | CDF |
|---|---|---|---|---|---|
| 1 | 200.00 | Aniso 350 | | n/a | n/a |
| 2 | 300.00 | Aniso 350 | | n/a | n/a |
| 3 | 300.00 | Aniso 240 | | n/a | n/a |
| 4 | 600.00 | Aniso 120 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 793 | 2.83E-03 | 5.22E+05 |

```
CIRCLY Version 5.0u (8 April 2013)

Job Title: A.2.1

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 793 U Title: Cat 793 Unloaded

   Load   Load          Movements
    No.   ID
    1     Cat 793 U     6.57E+05

Details of Load Groups:

   Load   Load         Load         Load             Radius    Pressure/
Exponent
    No.   ID           Category     Type                       Ref. stress
    1     Cat 793 U    Cat 793 Un   Vertical Force     389.0     0.70
0.00

   Load Locations:
   Location    Load         Gear          X          Y      Scaling     Theta
    No.        ID           No.                             Factor
    1          Cat 793 U     1             0.0        0.0   1.00E+00
0.00
    2          Cat 793 U     2          -423.0    -5905.0   1.00E+00
0.00
    3          Cat 793 U     2          1091.0    -5905.0   1.00E+00
0.00
    4          Cat 793 U     1          5630.0        0.0   1.00E+00
0.00
    5          Cat 793 U     2          4539.0    -5905.0   1.00E+00
0.00
    6          Cat 793 U     2          6053.0    -5905.0   1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: A.2.1 Title: Case Study A.2.1

   Layer  Lower    Material     Isotropy   Modulus    P.Ratio

    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Iso E350     Iso.       3.50E+02   0.35
    2     rough    Iso E350     Iso.       3.50E+02   0.35
    3     rough    Iso E240     Iso.       2.40E+02   0.35
    4     rough    Iso E120     Iso.       1.20E+02   0.35
    5     rough    Sub_CBR5 H   Aniso.     5.00E+01   0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component  Perform.   Perform.  Traffic
   No.             ID                      Constant   Exponent  Multiplier
    5     top      Sub 5 Per    EZZ         0.003100   10.269     1.000

   Reliability Factors: Not Used.


Results:

   Layer  Thickness  Material     Load          Critical       CDF
```

| No. | | ID | ID | Strain | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 200.00 | Iso E350 | | n/a | n/a |
| 3 | 200.00 | Iso E240 | | n/a | n/a |
| 4 | 500.00 | Iso E120 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 793 U | 1.47E-03 | 6.21E+02 |

```
CIRCLY Version 5.0u (8 April 2013)

Job Title: A.2.2

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 793 U Title: Cat 793 Unloaded

   Load   Load          Movements
    No.   ID
    1     Cat 793 U     6.57E+05

Details of Load Groups:

   Load   Load         Load         Load            Radius    Pressure/
Exponent
    No.   ID           Category     Type                      Ref. stress
    1     Cat 793 U    Cat 793 Un   Vertical Force    389.0    0.70
0.00

   Load Locations:
   Location   Load         Gear          X          Y      Scaling     Theta
    No.       ID           No.                             Factor
    1         Cat 793 U     1            0.0        0.0    1.00E+00
0.00
    2         Cat 793 U     2         -423.0    -5905.0    1.00E+00
0.00
    3         Cat 793 U     2         1091.0    -5905.0    1.00E+00
0.00
    4         Cat 793 U     1         5630.0        0.0    1.00E+00
0.00
    5         Cat 793 U     2         4539.0    -5905.0    1.00E+00
0.00
    6         Cat 793 U     2         6053.0    -5905.0    1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: A.2.2 Title: Case Study A.2.2

   Layer  Lower    Material     Isotropy   Modulus    P.Ratio

    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Iso E350     Iso.       3.50E+02   0.35
    2     rough    Iso E350     Iso.       3.50E+02   0.35
    3     rough    Iso E240     Iso.       2.40E+02   0.35
    4     rough    Iso E120     Iso.       1.20E+02   0.35
    5     rough    Sub_CBR5 H   Aniso.     5.00E+01   0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.            ID                      Constant   Exponent  Multiplier
    5     top      Sub 5 Per    EZZ         0.003100   10.269     1.000

   Reliability Factors: Not Used.


Results:

   Layer  Thickness  Material     Load         Critical       CDF
```

| No. | | ID | ID | Strain | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 200.00 | Iso E350 | | n/a | n/a |
| 3 | 250.00 | Iso E240 | | n/a | n/a |
| 4 | 450.00 | Iso E120 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 793 U | 1.46E-03 | 5.58E+02 |

```
CIRCLY Version 5.0u (8 April 2013)

Job Title: A.2.3

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 793 U Title: Cat 793 Unloaded

   Load   Load          Movements
    No.   ID
    1     Cat 793 U     6.57E+05

Details of Load Groups:

   Load   Load        Load        Load            Radius    Pressure/
Exponent
    No.   ID          Category    Type                      Ref. stress
    1     Cat 793 U   Cat 793 Un  Vertical Force    389.0    0.70
0.00

   Load Locations:
   Location   Load        Gear           X           Y      Scaling     Theta
    No.       ID          No.                               Factor
    1         Cat 793 U    1             0.0         0.0    1.00E+00
0.00
    2         Cat 793 U    2          -423.0     -5905.0    1.00E+00
0.00
    3         Cat 793 U    2          1091.0     -5905.0    1.00E+00
0.00
    4         Cat 793 U    1          5630.0         0.0    1.00E+00
0.00
    5         Cat 793 U    2          4539.0     -5905.0    1.00E+00
0.00
    6         Cat 793 U    2          6053.0     -5905.0    1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: A.2.3 Title: Case Study A.2.3

   Layer  Lower    Material     Isotropy   Modulus    P.Ratio

    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Iso E350     Iso.       3.50E+02   0.35
    2     rough    Iso E290     Iso.       2.90E+02   0.35
    3     rough    Iso E240     Iso.       2.40E+02   0.35
    4     rough    Iso E206     Iso.       2.06E+02   0.35
    5     rough    Sub_CBR5 H   Aniso.     5.00E+01   0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.            ID                      Constant   Exponent  Multiplier
    5     top      Sub 5 Per    EZZ         0.003100   10.269     1.000

   Reliability Factors: Not Used.


Results:

   Layer  Thickness  Material     Load          Critical       CDF
```

| No. | | ID | ID | Strain | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 200.00 | Iso E290 | | n/a | n/a |
| 3 | 200.00 | Iso E240 | | n/a | n/a |
| 4 | 500.00 | Iso E206 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 793 U | 1.36E-03 | 2.69E+02 |

```
CIRCLY Version 5.0u (8 April 2013)

   Z-value no.  1:  0
Job Title: A.2.3

Calculation of Selected Component at Selected z-values

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 793 U Title: Cat 793 Unloaded

   Load   Load         Movements
    No.   ID
    1     Cat 793 U    6.57E+05

Details of Load Groups:

   Load   Load        Load        Load             Radius    Pressure/
Exponent
    No.   ID          Category    Type                       Ref. stress
    1     Cat 793 U   Cat 793 Un  Vertical Force    389.0     0.70
0.00

   Load Locations:
   Location   Load        Gear          X          Y      Scaling     Theta
    No.       ID          No.                             Factor
    1         Cat 793 U    1             0.0        0.0   1.00E+00
0.00
    2         Cat 793 U    2          -423.0    -5905.0   1.00E+00
0.00
    3         Cat 793 U    2          1091.0    -5905.0   1.00E+00
0.00
    4         Cat 793 U    1          5630.0        0.0   1.00E+00
0.00
    5         Cat 793 U    2          4539.0    -5905.0   1.00E+00
0.00
    6         Cat 793 U    2          6053.0    -5905.0   1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: A.2.4 Title: Case Study A.2.4

   Layer  Lower    Material      Isotropy   Modulus    P.Ratio

    No.   i/face   ID                       (or Ev)    (or vvh)   F
Eh         vh
    1     rough    Iso E500      Iso.       5.00E+02   0.35
    2     rough    Iso E400      Iso.       4.00E+02   0.35
    3     rough    Iso E350      Iso.       3.50E+02   0.35
    4     rough    Iso E240      Iso.       2.40E+02   0.35
    5     rough    Sub_CBR5 H    Aniso.     5.00E+01   0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance   Component  Perform.   Perform.   Traffic
    No.            ID                       Constant   Exponent   Multiplier
    5     top      Sub 5 Per     EZZ         0.003100   10.269      1.000

   Reliability Factors: Not Used.
```

```
CIRCLY Version 5.0u (8 April 2013)

   Z-value no.  1:  0
Job Title: A.2.3

Calculation of Selected Component at Selected z-values

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 793 U Title: Cat 793 Unloaded

   Load   Load         Movements
    No.   ID
    1     Cat 793 U    6.57E+05

Details of Load Groups:

   Load   Load        Load        Load            Radius    Pressure/
Exponent
    No.   ID          Category    Type                      Ref. stress
    1     Cat 793 U   Cat 793 Un  Vertical Force    389.0    0.70
0.00

   Load Locations:
   Location   Load         Gear           X           Y       Scaling     Theta
    No.       ID           No.                                Factor
    1         Cat 793 U     1              0.0         0.0    1.00E+00
0.00
    2         Cat 793 U     2           -423.0     -5905.0    1.00E+00
0.00
    3         Cat 793 U     2           1091.0     -5905.0    1.00E+00
0.00
    4         Cat 793 U     1           5630.0         0.0    1.00E+00
0.00
    5         Cat 793 U     2           4539.0     -5905.0    1.00E+00
0.00
    6         Cat 793 U     2           6053.0     -5905.0    1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: A.2.5 Title: Case Study A.2.5

   Layer  Lower    Material     Isotropy   Modulus    P.Ratio

    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Iso E350     Iso.       3.50E+02   0.35
    2     rough    Iso E290     Iso.       2.90E+02   0.35
    3     rough    Iso E240     Iso.       2.40E+02   0.35
    4     rough    Iso E120     Iso.       1.20E+02   0.35
    5     rough    Sub_CBR5 H   Aniso.     5.00E+01   0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.            ID                      Constant   Exponent  Multiplier
    5     top      Sub 5 Per    EZZ         0.003100   10.269     1.000

   Reliability Factors: Not Used.
```

# Appendix G Case Study B CIRCLY Model Output Information

```
CIRCLY Version 5.0u (8 April 2013)

Job Title: B.1.1

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 789 Title: Cat 789

   Load   Load          Movements
    No.   ID
    1     Cat 789       1.58E+06

Details of Load Groups:

   Load   Load        Load        Load            Radius    Pressure/
Exponent
    No.   ID          Category    Type                      Ref. stress
    1     Cat 789     Cat 789     Vertical Force    538.0    0.70
0.00

   Load Locations:
   Location   Load        Gear          X          Y      Scaling     Theta
    No.       ID          No.                             Factor
    1         Cat 789      1            0.0        0.0    1.00E+00
0.00
    2         Cat 789      2         -240.0    -5700.0    1.00E+00
0.00
    3         Cat 789      2          992.0    -5700.0    1.00E+00
0.00
    4         Cat 789      1         5374.0        0.0    1.00E+00
0.00
    5         Cat 789      2         4382.0    -5700.0    1.00E+00
0.00
    6         Cat 789      2         5614.0    -5700.0    1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: B.1.1 Title: Case Study B.1.1

   Layer  Lower    Material     Isotropy   Modulus    P.Ratio

    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Iso E350     Iso.       3.50E+02   0.35
    2     rough    Iso E290     Iso.       2.90E+02   0.35
    3     rough    Iso E206     Iso.       2.06E+02   0.35
    4     rough    Sub_CBR5 H   Aniso.     5.00E+01   0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.            ID                      Constant   Exponent  Multiplier
    4     top      Sub 5 Per    EZZ         0.003100   10.269     1.000

   Reliability Factors: Not Used.


Results:

   Layer  Thickness  Material     Load          Critical       CDF
    No.              ID           ID            Strain
```

| | | | | | |
|---|---|---|---|---|---|
| 1 | 300.00 | Iso E350 | | n/a | n/a |
| 2 | 300.00 | Iso E290 | | n/a | n/a |
| 3 | 800.00 | Iso E206 | | n/a | n/a |
| 4 | 0.00 | Sub_CBR5 H | Cat 789 | 2.03E-03 | 4.09E+04 |

```
CIRCLY Version 5.0u (8 April 2013)

Job Title: B.1.2

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 789 Title: Cat 789

   Load   Load          Movements
    No.   ID
    1     Cat 789       1.58E+06

Details of Load Groups:

   Load   Load        Load        Load            Radius    Pressure/
Exponent
    No.   ID          Category    Type                      Ref. stress
    1     Cat 789     Cat 789     Vertical Force    538.0    0.70
0.00

   Load Locations:
   Location   Load        Gear          X          Y      Scaling     Theta
    No.       ID          No.                             Factor
    1         Cat 789      1             0.0        0.0   1.00E+00
0.00
    2         Cat 789      2          -240.0    -5700.0   1.00E+00
0.00
    3         Cat 789      2           992.0    -5700.0   1.00E+00
0.00
    4         Cat 789      1          5374.0        0.0   1.00E+00
0.00
    5         Cat 789      2          4382.0    -5700.0   1.00E+00
0.00
    6         Cat 789      2          5614.0    -5700.0   1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: B.1.2 Title: B.1.2

   Layer  Lower    Material     Isotropy   Modulus    P.Ratio

    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Iso E350     Iso.       3.50E+02   0.35
    2     rough    Iso E290     Iso.       2.90E+02   0.35
    3     rough    Iso E206     Iso.       2.06E+02   0.35
    4     rough    Sub_CBR5 H   Aniso.     5.00E+01   0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.            ID                      Constant   Exponent  Multiplier
    4     top      Sub 5 Per    EZZ         0.003100   10.269     1.000

   Reliability Factors: Not Used.


Results:

   Layer  Thickness  Material     Load          Critical      CDF
    No.              ID           ID            Strain
```

| | | | | | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 200.00 | Iso E290 | | n/a | n/a |
| 3 | 700.00 | Iso E206 | | n/a | n/a |
| 4 | 0.00 | Sub_CBR5 H | Cat 789 | 2.74E-03 | 8.86E+05 |

```
CIRCLY Version 5.0u (8 April 2013)

Job Title: B.1.3

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 789 Title: Cat 789

   Load   Load         Movements
    No.   ID
    1     Cat 789      1.58E+06

Details of Load Groups:

   Load   Load         Load         Load            Radius    Pressure/
Exponent
    No.   ID           Category     Type                      Ref. stress
    1     Cat 789      Cat 789      Vertical Force    538.0    0.70
0.00

   Load Locations:
   Location    Load         Gear          X          Y       Scaling     Theta
    No.        ID           No.                              Factor
    1          Cat 789       1            0.0        0.0     1.00E+00
0.00
    2          Cat 789       2         -240.0    -5700.0     1.00E+00
0.00
    3          Cat 789       2          992.0    -5700.0     1.00E+00
0.00
    4          Cat 789       1         5374.0        0.0     1.00E+00
0.00
    5          Cat 789       2         4382.0    -5700.0     1.00E+00
0.00
    6          Cat 789       2         5614.0    -5700.0     1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: B.1.3 Title: Case Study B.1.3

   Layer  Lower    Material     Isotropy   Modulus    P.Ratio

    No.   i/face   ID                      (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Iso E350     Iso.       3.50E+02   0.35
    2     rough    Iso E290     Iso.       2.90E+02   0.35
    3     rough    Iso E240     Iso.       2.40E+02   0.35
    4     rough    Sub_CBR5 H   Aniso.     5.00E+01   0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component  Perform.   Perform.  Traffic
    No.            ID                      Constant   Exponent  Multiplier
    4     top      Sub 5 Per    EZZ         0.003100   10.269     1.000

   Reliability Factors: Not Used.


Results:

   Layer  Thickness  Material     Load          Critical       CDF
    No.              ID           ID            Strain
```

| | | | | | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 200.00 | Iso E290 | | n/a | n/a |
| 3 | 700.00 | Iso E240 | | n/a | n/a |
| 4 | 0.00 | Sub_CBR5 H | Cat 789 | 2.62E-03 | 5.58E+05 |

CIRCLY Version 5.0u (8 April 2013)

Job Title: B.1.4

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: Cat 789 Title: Cat 789

| Load No. | Load ID | Movements |
|---|---|---|
| 1 | Cat 789 | 1.58E+06 |

Details of Load Groups:

| Load No. | Load ID | Load Category | Load Type | Radius | Pressure/ Ref. stress | Exponent |
|---|---|---|---|---|---|---|
| 1 | Cat 789 | Cat 789 | Vertical Force | 538.0 | 0.70 | 0.00 |

Load Locations:

| Location No. | Load ID | Gear No. | X | Y | Scaling Factor | Theta |
|---|---|---|---|---|---|---|
| 1 | Cat 789 | 1 | 0.0 | 0.0 | 1.00E+00 | 0.00 |
| 2 | Cat 789 | 2 | -240.0 | -5700.0 | 1.00E+00 | 0.00 |
| 3 | Cat 789 | 2 | 992.0 | -5700.0 | 1.00E+00 | 0.00 |
| 4 | Cat 789 | 1 | 5374.0 | 0.0 | 1.00E+00 | 0.00 |
| 5 | Cat 789 | 2 | 4382.0 | -5700.0 | 1.00E+00 | 0.00 |
| 6 | Cat 789 | 2 | 5614.0 | -5700.0 | 1.00E+00 | 0.00 |

Layout of result points on horizontal plane:
Xmin: -12500 Xmax: 20000 Xdel: 100
Y: 0

Details of Layered System:

ID: B.1.4 Title: Case Study B.1.4

| Layer No. | Lower i/face | Material ID | Isotropy | Modulus (or Ev) | P.Ratio (or vvh) | F | Eh | vh |
|---|---|---|---|---|---|---|---|---|
| 1 | rough | Iso E350 | Iso. | 3.50E+02 | 0.35 | | | |
| 2 | rough | Iso E290 | Iso. | 2.90E+02 | 0.35 | | | |
| 3 | rough | Iso E206 | Iso. | 2.06E+02 | 0.35 | | | |
| 4 | rough | Sub_CBR5 H | Aniso. | 5.00E+01 | 0.45 | 3.45E+01 | 2.50E+01 | 0.45 |

Performance Relationships:

| Layer No. | Location | Performance ID | Component | Perform. Constant | Perform. Exponent | Traffic Multiplier |
|---|---|---|---|---|---|---|
| 4 | top | Sub 5 Per | EZZ | 0.003100 | 10.269 | 1.000 |

Reliability Factors: Not Used.

Results:

| Layer No. | Thickness | Material ID | Load ID | Critical Strain | CDF |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 400.00 | Iso E290 | | n/a | n/a |
| 3 | 850.00 | Iso E206 | | n/a | n/a |
| 4 | 0.00 | Sub_CBR5 H | Cat 789 | 1.95E-03 | 2.76E+04 |

```
CIRCLY Version 5.0u (8 April 2013)

Job Title: B.1.5

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 789 Title: Cat 789

   Load   Load          Movements
    No.   ID
    1     Cat 789       1.58E+06

Details of Load Groups:

   Load   Load        Load        Load             Radius    Pressure/
Exponent
    No.   ID          Category    Type                       Ref. stress
    1     Cat 789     Cat 789     Vertical Force    538.0     0.70
0.00

   Load Locations:
   Location   Load        Gear          X           Y      Scaling     Theta
    No.       ID          No.                              Factor
    1         Cat 789      1            0.0         0.0    1.00E+00
0.00
    2         Cat 789      2         -240.0     -5700.0    1.00E+00
0.00
    3         Cat 789      2          992.0     -5700.0    1.00E+00
0.00
    4         Cat 789      1         5374.0         0.0    1.00E+00
0.00
    5         Cat 789      2         4382.0     -5700.0    1.00E+00
0.00
    6         Cat 789      2         5614.0     -5700.0    1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: B.1.5 Title: Case Study B.1.5

   Layer  Lower    Material     Isotropy    Modulus     P.Ratio

    No.   i/face   ID                       (or Ev)     (or vvh)   F
Eh         vh
    1     rough    Iso E350     Iso.        3.50E+02    0.35
    2     rough    Iso E3000    Iso.        3.00E+03    0.35
    3     rough    Sub_CBR5 H   Aniso.      5.00E+01    0.45       3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component   Perform.    Perform.   Traffic
    No.            ID                       Constant    Exponent   Multiplier
    3     top      Sub 5 Per    EZZ          0.003100    10.269      1.000

   Reliability Factors: Not Used.


Results:

   Layer  Thickness  Material     Load          Critical       CDF
    No.              ID           ID            Strain
    1      200.00    Iso E350                    n/a           n/a
```

| | | | | | |
|---|---|---|---|---|---|
| 2 | 780.00 | Iso E3000 | | n/a | n/a |
| 3 | 0.00 | Sub_CBR5 H | Cat 789 | 1.09E-03 | 6.95E+01 |

CIRCLY Version 5.0u (8 April 2013)

Job Title: B.1.5

Damage Factor Calculation

Assumed number of damage pulses per movement:
One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

ID: Cat 789 Title: Cat 789

| Load No. | Load ID | Movements |
|---|---|---|
| 1 | Cat 789 | 1.58E+06 |

Details of Load Groups:

| Load No. | Load ID | Load Category | Load Type | Radius | Pressure/ Ref. stress | Exponent |
|---|---|---|---|---|---|---|
| 1 | Cat 789 | Cat 789 | Vertical Force | 538.0 | 0.70 | 0.00 |

Load Locations:

| Location No. | Load ID | Gear No. | X | Y | Scaling Factor | Theta |
|---|---|---|---|---|---|---|
| 1 | Cat 789 | 1 | 0.0 | 0.0 | 1.00E+00 | 0.00 |
| 2 | Cat 789 | 2 | -240.0 | -5700.0 | 1.00E+00 | 0.00 |
| 3 | Cat 789 | 2 | 992.0 | -5700.0 | 1.00E+00 | 0.00 |
| 4 | Cat 789 | 1 | 5374.0 | 0.0 | 1.00E+00 | 0.00 |
| 5 | Cat 789 | 2 | 4382.0 | -5700.0 | 1.00E+00 | 0.00 |
| 6 | Cat 789 | 2 | 5614.0 | -5700.0 | 1.00E+00 | 0.00 |

Layout of result points on horizontal plane:
Xmin: -12500   Xmax:  20000   Xdel:  100
Y:     0

Details of Layered System:

ID: B.1.6 Title: Case Study B.1.6

| Layer No. | Lower i/face | Material ID | Isotropy | Modulus (or Ev) | P.Ratio (or vvh) | F | Eh | vh |
|---|---|---|---|---|---|---|---|---|
| 1 | rough | Iso E500 | Iso. | 5.00E+02 | 0.35 | | | |
| 2 | rough | Iso E400 | Iso. | 4.00E+02 | 0.35 | | | |
| 3 | rough | Iso E350 | Iso. | 3.50E+02 | 0.35 | | | |
| 4 | rough | Sub_CBR5 H | Aniso. | 5.00E+01 | 0.45 | 3.45E+01 | 2.50E+01 | 0.45 |

Performance Relationships:

| Layer No. | Location | Performance ID | Component | Perform. Constant | Perform. Exponent | Traffic Multiplier |
|---|---|---|---|---|---|---|
| 4 | top | Sub 5 Per | EZZ | 0.003100 | 10.269 | 1.000 |

Reliability Factors: Not Used.

Results:

| Layer No. | Thickness | Material ID | Load ID | Critical Strain | CDF |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E500 | | n/a | n/a |
| 2 | 200.00 | Iso E400 | | n/a | n/a |
| 3 | 700.00 | Iso E350 | | n/a | n/a |
| 4 | 0.00 | Sub_CBR5 H | Cat 789 | 2.22E-03 | 1.01E+05 |

```
CIRCLY Version 5.0u (8 April 2013)

Job Title: B.1.5

Damage Factor Calculation

Assumed number of damage pulses per movement:
   One pulse per axle (i.e. use NROWS)

Traffic Spectrum Details:

   ID: Cat 789 Title: Cat 789

   Load   Load         Movements
    No.   ID
    1     Cat 789      1.58E+06

Details of Load Groups:

   Load   Load        Load        Load            Radius    Pressure/
Exponent
    No.   ID          Category    Type                      Ref. stress
    1     Cat 789     Cat 789     Vertical Force    538.0    0.70
0.00

   Load Locations:
   Location   Load        Gear          X          Y      Scaling     Theta
    No.       ID          No.                             Factor
    1         Cat 789      1             0.0        0.0   1.00E+00
0.00
    2         Cat 789      2          -240.0    -5700.0   1.00E+00
0.00
    3         Cat 789      2           992.0    -5700.0   1.00E+00
0.00
    4         Cat 789      1          5374.0        0.0   1.00E+00
0.00
    5         Cat 789      2          4382.0    -5700.0   1.00E+00
0.00
    6         Cat 789      2          5614.0    -5700.0   1.00E+00
0.00

Layout of result points on horizontal plane:
   Xmin: -12500   Xmax:  20000   Xdel:  100
   Y:     0

Details of Layered System:

   ID: B.1.7 Title: Case Study B.1.7

   Layer  Lower    Material     Isotropy    Modulus    P.Ratio

    No.   i/face   ID                       (or Ev)    (or vvh)  F
Eh         vh
    1     rough    Iso E350     Iso.        3.50E+02   0.35
    2     rough    Iso E290     Iso.        2.90E+02   0.35
    3     rough    Iso E240     Iso.        2.40E+02   0.35
    4     rough    Iso E120     Iso.        1.20E+02   0.35
    5     rough    Sub_CBR5 H   Aniso.      5.00E+01   0.45      3.45E+01
2.50E+01   0.45

   Performance Relationships:
   Layer  Location Performance  Component   Perform.   Perform.  Traffic
    No.            ID                       Constant   Exponent  Multiplier
    5     top      Sub 5 Per    EZZ          0.003100   10.269     1.000

   Reliability Factors: Not Used.


Results:

   Layer  Thickness  Material     Load         Critical       CDF
```

| No. | | ID | ID | Strain | |
|---|---|---|---|---|---|
| 1 | 200.00 | Iso E350 | | n/a | n/a |
| 2 | 200.00 | Iso E290 | | n/a | n/a |
| 3 | 300.00 | Iso E240 | | n/a | n/a |
| 4 | 400.00 | Iso E120 | | n/a | n/a |
| 5 | 0.00 | Sub_CBR5 H | Cat 789 | 2.95E-03 | 1.87E+06 |