University of Alberta

Impact of hauler scale in mine planning

by

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Dedications

This thesis is dedicated to my husband Allen Matari and our son Nathan Mellan Matari.

Thank you for the love, support, encouragement, patience and understanding during the whole time of my studies.

ABSTRACT

Equipment selection is one of the most important decisions made in mine planning. Size of equipment affects decisions from size of pit to total cost of operation. There are some factors in equipment size selection which are currently incorporated into mine planning process and others are not.

This study analyses hauler scale impacts on aspects not incorporated into conventional mine planning including expansion of roads to accommodate larger equipment, road layer thickness variation depending on hauler size, the rate of increase of rolling resistance and fuel consumption and emissions. Results obtained indicate a huge impact in cost and therefore their consideration in mine planning is highly recommended.

Acknowledgement

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SYMBOLS AND ABBREVIATIONS

#	-	Number
$	-	Dollar
%	-	Percentage
Δ	-	Change
a	-	Acceleration
A	-	Area
AASHTO	-	Association of State Highway Transportation Official's System
b	-	Equivalent tire width
CAT	-	Caterpillar
CBR	-	California Bearing Ratio
D	-	Days
DDC	-	Detroit Diesel Corporation
ε	-	Strain
EBM	-	Economic block model
EBV	-	Economic block value
E_r	-	Resilient modulus
EVW	-	Empty vehicle weight
F	-	Force
g	-	Gravity
GC	-	Grading coefficient
GR	-	Grade resistance
GVW	-	Gross vehicle weight
HC	-	Hydrocarbons
KPa	-	Kilo Pascal (N/m^2)
KT	-	Kilo-tonnes
kW	-	Kilo-watt
kWh	-	Kilowatt-hour
m	-	Mass

MPa	-	Mega Pascal (N/m^2)
NOx	-	Oxides of nitrogen
NPV	-	Net present value
OEM	-	Original equipment manufacturer
PI	-	Plasticity index
PM	-	Particulate matter
ROI	-	Return on investment
RR	-	Rolling resistance
SP	-	Shrinkage product
t	-	Tonne
ton	-	Short ton
TR	-	Total resistance
UCSC	-	Unified Soil Classification System
USBM	-	United State Bureau of Mines
V	-	Volume
V_0	-	Velocity
δ	-	Tire stain
ϕ	-	Tire diameter
σ	-	Tire stress

1 INTRODUCTION

1.1 Overview

The size of mining equipment especially trucks continues to increase. Under a prevailing mentality that bigger is better, mine operations favour use of bigger equipment. Mines are thinking of phasing out smaller equipment and replace by bigger ones. Some improvements have been seen in reduction of cost per tonne and increased productivity due to increased capacity. There are however challenges associated with bigger size equipment affecting mine planning that have not been addressed and which ultimately move economics adversely on overall mine project.

Major challenges formally discussed around bigger equipment are associated with selectivity and higher capital investment. There are more issues not yet analysed by others and their effects yet to be quantified, which are equally important and have huge impact in mine planning.

Size of haul roads impacts directly the size of the pit and waste stripping. Costs of haul road design, construction and maintenance depend on size of roads which in turn are influenced by truck size; bigger trucks cause these costs to go up. Deterioration of quality of roads due to weight and motions imposed by the trucks raise rolling resistance which affect performance, safety and operating costs of trucks.

The costs associated with truck operations such as tires, maintenance and fuel consumption are also influenced by size of truck. Diesel emissions are influenced the amount of fuel consumed and engine efficiency. Better understanding of these factors, quantifying their impacts and incorporating them into mine planning is important to ensure improved planning practice.

1.2 Research objective

In the mine planning process; equipment size is traditionally considered as a tool to meet the production rate anticipated. Selection of loading equipment is based on production requirements and digging conditions. Also selection of haul trucks depends on haul road alignment, distance between loading and dumping destinations and should be matched to loading equipment within availability and utilization restrictions. There are more areas affected by equipment selection, particularly haulers, which are not currently incorporated in planning process or other planning considerations.

The objective of this research is to determine the hauler scale impact in mine planning touching some major areas which have been ignored. It focuses on aspects such as road size (the increase in stripping ratio) and road construction requirements as the function of hauler size, the estimate of rate of increase of rolling resistance and the corresponding fuel consumption and diesel emissions as the result of hauler size.

To quantify the impact of each aspect, the dollar value for each is attached referencing 2012 operating costs in Alberta. These values used are at least relative as it is hard to focus on a single dollar value. Emissions have a huge environmental and health impact which is considered qualitative but in reference to fuel use a cost may be applied.

1.3 Research approach

The approach used in this study was to review the literature on mine planning and equipment selection; especially the advantages and challenges of hauler size in mine operations.

The analysis of the impact of hauler scale was then evaluated for aspects of road design, construction and deterioration of road quality (rolling resistance) affecting fuel consumption and emissions. Already established approaches were reviewed for road design, construction and analysis of rolling resistance increase. For fuel consumption and emissions, information gathered from the literature and was used to establish relationships to hauler size.

For comparison, three truck models of varying size from the same OEM were used (CAT 785C, CAT 793F and CAT 797F). To ensure a reasonable comparison, similar operating conditions and production requirements were assumed.

This study was undertaken to help mine planners when deciding on equipment size during the initial planning process, during mine operations and when the need for equipment replacement or upgrade arises.

1.4 Research limitations

The study was conducted from data obtained from OEMs and previous operational field data acquired from oil sand operations at an average ambient temperature of 20^0C (spring through fall seasons).

For the design of road pavement thickness, static loads were used. Dynamic evaluations would cyclically increase ground loading up to an additional 50% with 1.5g events. For future work these variations should be considered.

Cost evaluations were performed using data from mine sites in Alberta. Snapshot constant values were used ignoring interest rates and cost variation with time. As this research work illustrates a methodology of considering the impact of increasing hauler size, the economic comparison was taken as an example "snapshot" only.

RESEARCH BACKGROUND

2 MINE PLANNING

2.1 Introduction

The prime objective of any mining operation is the extraction of a mineral deposit at the lowest possible cost to maximize profit and net present value. Selection of physical design parameters and scheduling of ore and waste extraction are complex engineering decisions that have significant impact on economic viability of any operation. Mine planning is therefore an economic exercise constrained by geologic, technical and operational aspects to ensure the economic objective of a mine operation is achieved (Nasab, 2011).

Mine planning objectives should ensure a realistic and actionable plan to extract the mineral deposit profitably. To ensure that; a mine plan reflects the ultimate pit limit within which the mineral can be extracted profitably as well as schedule the sequence of ore mining and waste stripping over time to deplete the reserve to the design pit limits defined by an ultimate stripping ratio. Decision on production rate, size of equipment and fleet size is important, focusing on deposit characteristics and mineral extraction method and capacity to ensure profitable operation.

These decisions are made simultaneously and reflect a great uncertainty in geotechnical conditions, geological composition, mining and processing recoveries as well as market commodity price and the costs associated with mining and processing (Whittle, 2011). Due to the uncertainties in input data, mine planning tasks are done over and over again evaluating sensitivity, redefining and confirming key assumptions and incorporating new available information as it arises.

Equipment size has a major impact on mine planning. It is estimated that nearly 50% of mining cost comes from loading and hauling activities. Pit geometry and stripping ratio, haul road sizes, dumping destination, crusher dumping points and other infrastructure are all affected by the size of equipment used. Therefore selection of equipment is a critical decision made during planning, as it impacts greatly the economics of the project. The selection should not only be made to suit the agreed on production rate but should also be focused on economic implications of the selection. The geomechanical and environmental conditions play a huge role in equipment performance affecting all other concerns.

Note: In the mining industry stripping ratio is the ratio of overburden (waste) stripped to the ore mined. In considering road size, stripping was considered as the additional waste required to be mined to accommodate an incremental increase in the size of the road.

2.2 Mine planning process

The mine planning process is an engineering process of ensuring profitable mining and processing of the mineral. The purpose of mine planning is to add value to the resource taking into account the deposit and modifying factors. These factors include market of the product, metallurgical processing and recoveries, mine method, corporate objectives, environmental issues as well as political constraints. The process can be done once or iteratively depending on availability of new information about the deposit and operability factors, with potential improvement in every iteration.

The outcomes of mine planning are decisions on pit design, mine sequencing, production rate, mine equipment, ore selection and processing method. Generally, the mine planning process includes;

i. Resource estimation

A resource estimate is based on prediction of the spatial characteristics of a mineral deposit through collection of data, analysis of that data, and modeling the size, shape, and grade of the deposit. Important spatial characteristics of the ore body predicted include the size, shape, and continuity of ore zones, the distribution of mineral grade, and spatial variability of mineral grade. These spatial characteristics of the mineral deposit are never completely known but are inferred from the drilled hole sample data (Noble, 1992)

ii. Ore body modelling

The model is formulated by dividing the ore body into fixed or variable size blocks. The size of the blocks depends on physical characteristics of the mine such as dip of the deposit, variability of ore grades, dependence on geotechnical performance within rock structure, pit slopes and equipment used; therefore the considerations of equipment size start early. The grade assignment depends on the drill hole data analysis through geostatistics. Techniques such as distance weighted interpolations, regression analysis, weighted moving averages and Kriging are used for this purpose.

iii. Economic block model

An economic block model (EBM) is constructed by estimating the value for every block in the model referred to as an economic block value (EBV). The value depends on the metal content in the block, its location relative to the surface and the cost associated with production, processing and refining. However it is rare to have more than rough estimates of cost for a project at this stage. The net value for each block is obtained by subtracting the costs from the revenue generated for a particular block. Revenue is estimated from ore tonnage and grade from the block model, mining and processing recoveries as well as product price. However, market changes are difficult to predict and therefore add uncertainty to the process. Cost is impacted by equipment size, therefore the idea of equipment size is critical in formulating an EBM or at least understanding the impact of scale on such associated costs.

$$EBV = \mathrm{Re}venue - Cost \tag{2-1}$$

iv. Ultimate pit limit

For any ore body there are many feasible outcomes. The optimal outline is defined as one with the maximum dollar value at an acceptable pit slope i.e. nothing can be increased without breaking the slope constraints or left without reducing the pit value. The standard algorithm for finding an ultimate pit limit used in the industry today is the Lerch- Grossman algorithm or the floating cone method which is mathematically proven to generate an acceptable solution. Two commercial software packages using this algorithm are Whittle and NPV scheduler (Nasab, 2011). Locations and size of ramps and bench orientation should be considered in any optimization to ensure minimum deviation in designing the pit outline.

The outline generated is one of the tools used in deciding the mineral reserve at least in a prefeasibility study. It is also used in evaluating economical potential of the deposit, financing the business and taxation, short term and long term mine plans and locating the boundaries beyond which other infrastructures can be located. The input variables are estimated values and uncertain, so the optimal pit outline may change at times depending on changes in input variables. These variables include; overall pit slopes in different areas, mining and processing costs, mining and processing recoveries, selling price etc.

v. Pushback planning

A pushback is a feasible increment of a pit over time. Push-backs are designed to extend the limits of economic ore. An ore reserve is calculated with stripping requirements for pushbacks to a final pit limit. These outlines may also change depending on input parameters used for the optimization process and decision on changing equipment size.

vi. Open pit scheduling

The mine scheduling process defines a mining sequence over the life of the mine and stipulates the amount of ore, waste and specific blocks that will be mined each year so that the highest economic return can be obtained under a number of constraints. These constraints are:

- Pit slope variations including stripping ratio (SR)
- Volume of material extracted per period and "dropdown rate" (rate at which a pit is mined out)
- Size and quantity of equipment with their associated availabilities and utilizations which will change with time
- Mill throughput (mill feed and mill capacity) and
- Blending constraints

The life of mine is determined as the time required to exhaust the whole reserve within a defined schedule, which indicates equipment requirements throughout. Equipment capacities and lifespan are important at this stage. When planning and scheduling are completed, a range of viabilities for a project are determined.

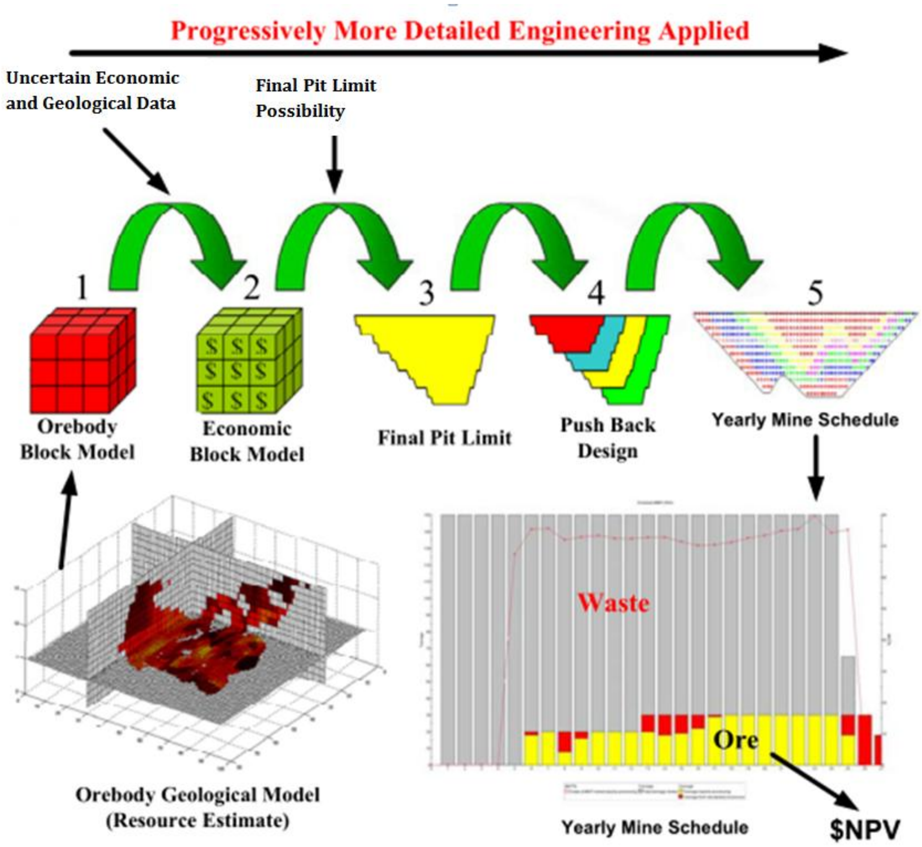


Figure 2-1: Simplified flowchart of strategic mine planning process (after Nasab, 2011)

2.3 Integrating fleet size to mine planning.

Equipment selection affects mine planning, capital and production costs. Pit optimization and production strategy depends on type and size of equipment used. According to Bozorgebrahimi (2004) equipment optimization and pit optimization are strongly linked. An optimum pit limit is assumed to be achieved whenever some economic criteria, such as return on investment (ROI), is acceptable. Improved equipment selection will lower mining costs and change the optimized pit limits.

On the other hand, production strategy is one of the major decisions made in mine planning after understanding deposit characteristics to ensure supply of ore and required stripping depending on market conditions. This leads to decisions on;

- Ore and waste production rates in conjunction with the available reserve and market conditions
- Selectivity, depending on the type of deposit and equipment used
- Blending requirements and
- Number of working places, which is the function of a market driven production.

Type of material to be loaded, ground conditions and material destination all influence the type, size and quantity of equipment required to profitably accomplish production requirements. One of the major costs in an open pit mine operation is associated with loading and hauling. Therefore cost comparisons by type and equipment size alternatives need to be critically analyzed in selection of these fleets.

2.4 Equipment sizing

Singhal (1986) suggests that size selection criteria for loading and haulage machines are not the same. The mining selectivity, productivity, reliability and flexibility are essential factors for loading machine selection. On the other hand the size of the haulage equipment influences mine layout and design while being also matched to loading equipment. Selection criteria for haulage equipment are performance, flexibility, haul road conditions, distance travelled and haulage capacity.

Loading equipment size is based on daily production and potential operating conditions related to maintenance, utilization and mine layouts focused on minimizing mining costs. According to Lizzote, (1988) the equipment selection process consists of first choosing the type of the equipment, then sizing the equipment and finally determining the number of units required to meet a selected production rate permitting a match between loading and haulage equipment.

A common method used to size loading equipment is to compute dipper capacity. According to Berkhimer (2011) production rates can be converted into loose volume per hour units to allow the calculation of required bucket size.

$$Q = \frac{P \times T}{3600 \times BF \times U \times A} \qquad (2\text{-}2)$$

Where Q is the bucket (dipper) capacity, P is the required production (loose volume per hour), T is the theoretical cycle time, BF is the bucket fill factor, U is equipment utilization, and A mechanical availability expected over the period of operation.

The performance of the entire hauling system is controlled by the availability and utilization of the loading equipment. In all cases, shovels play a key role in a performance decision. This is due to the simple fact that shovels are more expensive with longer life, depending on size. The haulage equipment needs to be matched with the loading machine. By "rule of thumb" the number of passes required to fill a truck ranges from 3 to 5 passes, if ore selectivity is not an issue. If selective high value ore deposits, like gold are being mined, the number of passes can be as high as 20 passes per truck.

The dimensions of a machine and its production rate are important factors in equipment sizing. Larger dimensions and increased productivity do not necessarily go hand-in-hand. The speed of each component in a digging cycle and dimensions such as dumping height influence loading machine productivity and must also be taken in consideration.

The use of larger trucks in a fleet with smaller sized loading equipment would increase loading time. The ability to reach into a truck box and create a good balanced load distribution in the box could be a problem, resulting in detrimental impacts on the truck body, suspension, tires frames and dynamic truck performance; not to mention the operator's health. On the other hand, if larger loading machines are used with smaller capacity trucks; excess bucket loads will have a damaging overload impact on the structure and suspension systems of these trucks.

2.5 The evolution of equipment sizes

In the past 60 years mining equipment has increased in size and capacity, particularly haul trucks under the assumption that "bigger is better". For example, the 400 ton trucks of today are more than 10 times the size of the 35ton trucks of the 1950s. Experience has shown that larger equipment has reduced total overall cost by improving productivity in some big mines, (Baumann, 1999). Decline in commodity prices at the close of the 20th Century and sharp a rise in demand for mineral commodities in recent years are two factors which perpetuate the use of larger equipment to lower unit costs and get commodities out of the ground faster (Gilewicz, 2001). Sometimes this theory does not match reality; only a few years later, after 'bigger is better' adage popularity, a haulage forum rearranged the words and asked, "Is bigger better?" The answer coming out of that conference was: "It depends" (Berkhimer, 2011)

Table 2-1: Evolution on mine equipment in the past 40 years (Caterpillar, 2012 and Dietz, 2000)

Year	shovels (yd^3)	Trucks payload (tons)
1970	15	70
1985	46	150
2000	67	360
2012	88	400

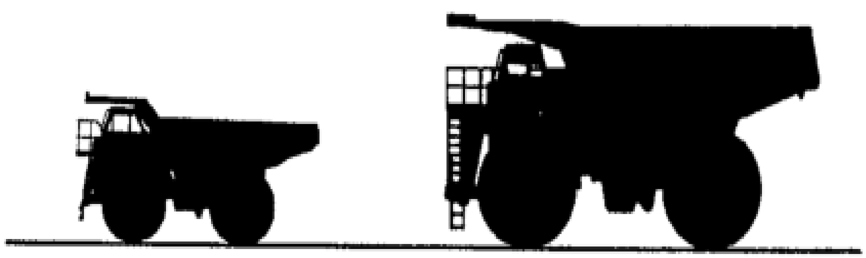


Figure 2-2: Comparative profiles of 400ton and 100ton capacity trucks (Caterpillar, 1999**)**

2.5.1 Transition to bigger equipment

Evolution of the mining industry to accommodate larger equipment is a demanding process; some mines are unable to grow past a certain size for the larger equipment to overcome the effects of expansion and be economical. Boucom (2011) categorized mine site equipment evolution in 3 groups based on the ability for a mine to accommodate larger equipment (trucks beyond the 240 ton class). He specified conditions which limit the application of such equipment as mine design geometry, mining selectivity, pit layout, crusher dump widths and infrastructure such as shop size and bay door widths. These groups are; (a) mines with hard constraints, (b) mines with soft constraints and (c) Greenfield mines with minimal constraints as they are at the beginning of a project.

Mines with hard constraints are the ones where it is cost prohibitive, geologically and/or physically impossible to operate with larger trucks. Mine design, and infrastructure act as hard capital constraints for mines to grow and accommodate larger equipment.

Mines with soft constraints consist of mines that were initially designed to accommodate medium sized trucks (240ton), for which the logical step is an incremental increase in size. Estimates for infrastructure requirements are typically conservative enough that this step is not impractical and would not require significant capital investment to broaden application.

Greenfield mines are the mines that have not yet been developed. Greenfield operations with high production potential may be able to accommodate ultra-class trucks and rope shovels depending on ore body extent; as they can design their pits and infrastructure to accommodate larger equipment allowing cost/t to ultimately be lower although initial capital investment will be very high (Boucom, 2011). Therefore, transition from small to larger equipment size depends on ability to extend the operating pit dimensions and other infrastructures without affecting profitability, otherwise the adaptation may be extremely challenging.

2.5.2 Equipment size advantages and challenges

Transition to larger equipment has been believed to lower production cost and increasing production capacity and many mines have transitioned to bigger equipment while others are considering the option. On the other hand this has not always been the case; there are more challenges in adopting bigger equipment, whose impacts need to be considered in decision making.

i. Bigger equipment advantages

One of the biggest advantages of operating larger equipment is the reduction of cost per tonne. This has been made possible through increased levels of mechanization, automation and higher capacity. Cost reduction has been achieved by reduction of the labor force required in operating and maintaining larger equipment, increasing production capacity and maintenance efficiencies, reduction of truck energy consumption per tonne and reduction of maintenance costs per tonne.

Higher engine power which also results in higher power to weight ratios is another advantage of larger equipment. In fact, the larger the haul truck, the faster it can travel an identical distance (Boucom, 2011). The higher engine power indicates that these trucks are able to travel much faster, particularly loaded uphill than their smaller counterparts. This leads to a situation where in a mixed fleet of trucks, bigger trucks are being slowed down on a ramp by smaller trucks.

ii. Bigger equipment Challenges

Apart from the compatibility to the size of the operation and the capital cost to acquire, there are more challenges associated with bigger equipment. Increasing levels of complexity with larger capacity equipment may result in increased maintenance costs resulting in lower availability. Demand for skilled and educated personnel together with special tools for maintenance of fewer more complex and larger equipment increases maintenance cost.

Lack of redundancy through production losses incurred when bigger equipment breakdowns are a challenge as discussed by Krause (2001) and Roman and Daneshmand, (2000). When it comes to maintenance cost, (Roman and Daneshmand, 2000) suggest that maintenance cost does not go down because there are fewer trucks in the fleet to maintain. The cost of lost production due to breakdown maintenance is higher with larger equipment and can potentially be greater than the savings achieved from this fleet.

As illustrated in figure 2-3 downtime cost due to breakdowns consists of the repair cost (including parts and labour) plus the cost of the lost production due to failure. Plotting total downtime cost per truck as the sum of these two component costs, we see that the total downtime cost per truck for the low capacity fleet of smaller truck size is much lower than that associated with a high capacity fleet of larger truck size.

The economics of open pit mines are sensitive to road width. Any change in the road width directly influences the overall pit wall slope and the stripping ratio. Bigger trucks need wider haul roads which means more stripping. This is quite an issue with deep pits requiring advancing high-walls to accommodate haul roads (Krause, 2001).

The quality of haul road running surfaces are a concern with increasing size and weight of the trucks, as the roads get cyclically worked especially with soft underfoot conditions such as exists in oil sand operations. With increasing rolling resistance, the truck speed and productivity, truck maintenance, fuel consumption and tire life are highly impacted.

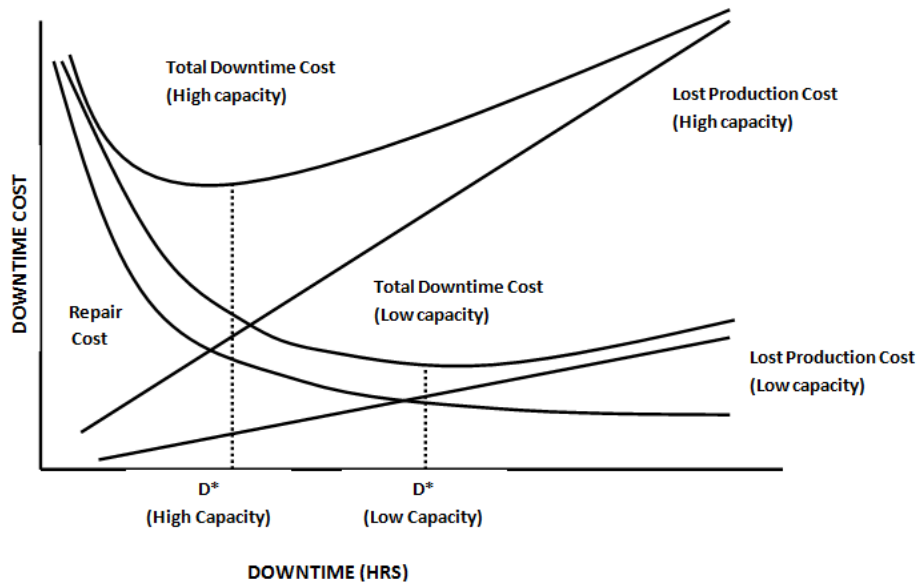


Figure 2-3: Effects of larger equipment capacity on downtime costs (after Roman & Daneshmand, 2000)

Other challenges include the increase in size of infrastructure such as the size of maintenance facility, bay doors and crane heights, and supporting equipment such as graders. Dumping points (hoppers) increase too. In terms of environmental impacts, the use of larger equipment results in earlier production and processing of extra waste. This makes waste management more costly and complicated due to greater land requirements to accommodate early additional waste dumps and tailing dams which transform into higher capital and operating costs.

For safe operation of equipment, pit benches and bottoms need to be wide enough to accommodate the size of loading equipment via turning radii, truck dimensions, safety berms and manoeuvring space for multiple units. Operating bigger equipment necessitates bigger pit bottoms and therefore overall greater stripping ratios are required.

2.6 Chapter conclusion

This chapter reviewed conventional mine planning process focusing on consideration of equipment size. Mostly, equipment size is considered as a tool to achieve production, taking into account deposit characteristics and mineral extraction methods and capacity. The 'bigger is better' notion was discussed with advantages and challenges of employing bigger equipment, as discussed by different researchers active in the industry.

The effect of truck size on road size, road construction requirements, rolling resistance increase and fuel consumption and emissions are not thought of in the current conventional mine planning process. That is why this study was undertaken to quantify their effects and see the importance of incorporating into mine planning focusing on their subsequent impacts.

LITERATURE REVIEW

3 HAUL ROAD CONSTRUCTION

One of the major requirements for truck haulage are roads. Road construction can be divided into four major categories. Geometric design deals with road layout and alignment. Structural design deals with pavement construction and layer thickness while functional design focuses on construction material selection. The last category is maintenance design which focuses on maintenance management to ensure overall lower costs for the road user i.e. balancing between maintenance frequency and the impact on trucks due to increasing road deterioration (reflected by an increase in rolling resistance).

3.1 Haul road geometric design

Geometric design is commonly the starting point for any haul road design. It refers to the layout and alignment of the road, in the both horizontal and vertical planes, stopping distances, sight distances, junction layouts, berm walls, provision of shoulders and road width variation within the limits imposed by the mining method. The ultimate aim is to produce an efficient and safe geometric design.

i. Road Widths

Road width is function of the size of truck used. In most cases, a straight stretch of road will be 3 to 4 times the width of the widest heavy hauler with more width on the corners to allow for vehicle overhang (car length extending beyond wheel base). The minimum width of running surface for the straight sections of single and multi-lane roads can be determined from the following expression according to Tannant & Regensburg (2001);

$$W = (1.5L + 0.5)X \qquad \textbf{(3-1)}$$

Where;

W = width of running surface (m)

L = number of lanes

X = vehicle width (m).

For switchbacks and other sharp curves and/ or roads with high traffic volume or limited visibility, a safe road width should be designed with an additional 0.5 times width of the vehicle (Thompson, 2011a).

$$W = (1.5L + 1)X \tag{3-1a}$$

ii. Maximum and Sustained Grade

Grade of roads is a function of safety and economics. In most cases, grades will vary between 0 and 8% on long hauls and may approach 12% on short hauls. However, most of mine ramps will have a grade between 6% and 10%. With ultra-class trucks the grade of less than 6% is more favourable especially for soft underfoot conditions like oil sands (Tannant & Regensburg, 2001).

iii. Curves and Switchbacks

Curve and switchback design should take into account sight distance, minimum vehicle turning radius and truck performance. It should be designed with the maximum radius possible (generally >200m ideally) and be kept smooth and consistent. According to Thompson (2011a), minimum curve radius (R (m)) can be initially determined from;

$$R = \frac{v_0^2 + U_{\min} * e}{127e} \tag{3-2}$$

Where;

e = super-elevation applied (m/m width of road)

U_{min} = coefficient of lateral friction tyre-road

v_o = vehicle speed (km/h)

U_{min}, the coefficient of lateral tyre-road friction, is usually taken as zero for wet, soft, muddy to 0.20 for dry, compacted gravel surface (Thompson, 2011a).

3.1.1 Impact of truck size to size of the road

The increase in truck size requires wider roads which necessitate higher stripping ratios in open pit mines. Pit wall slope decreases when size of a ramp increases as described in figure 3-1.

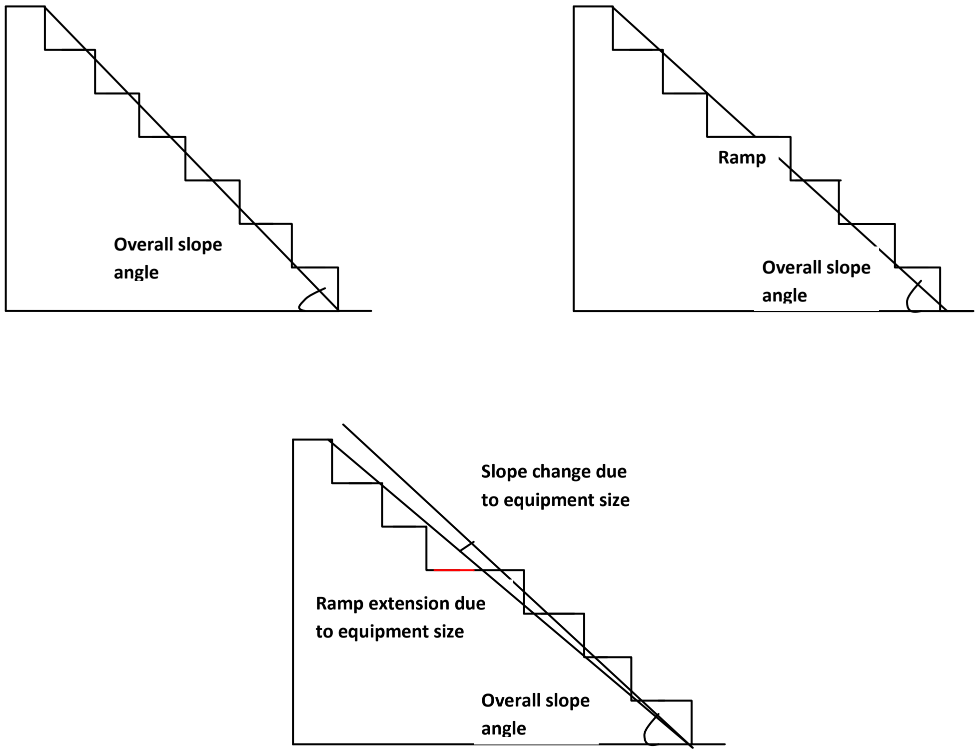


Figure 3-1: Effect of equipment size on pit slope (After Bozorgebrahimi 2004)

According to Bozorgebrahimi (2004), the additional pit slope due to implementation of larger trucks can be calculated using the following formulae in equation 3-3 to 3-7;

$$\Delta\alpha = \tan^{-1}\left(\Delta x \times \sin(\alpha) / y\right) \quad \textbf{(3-3)}$$

$$\Delta\alpha = \tan^{-1}\sum_{1}^{n}(\Delta x) \times \sin(\alpha) / y \quad \textbf{(3-4)}$$

Where,

$$n = INT\left[g^{-1} \times \frac{PD}{LR}\right] \quad \textbf{(3-5)}$$

where PD is the pit depth, LR is the length of pit wall the ramp occupies, Δx is the road width increase required to use larger trucks (m), Δα is the overall pit slope decrease from implementing larger trucks in degrees, α is the overall pit slope before implementing larger trucks in degrees, n is the number of times that the ramp cuts (crosses) the pit wall (determined from Eq 3-5), y is the pit depth (m), and g ramp grade (%).

The weight, W of material to be mined due to ramp widening is given by the following equation

$$W = \int_0^{\frac{Y}{g}} \int_0^{Y} (0.5 \times \gamma \times \Delta x) dhdl \quad \textbf{(3-6)}$$

Where γ is the average specific weight of the materials to be mined, Δx is the width of the ramp widening, dh is an element of pit depth, dl is an element of the length of the ramp, g is the ramp grade (%), and Y is the maximum depth of pit which the ramp is to reach.

Solving Eq. 3-6 gives:

$$W = (0.5 \times \gamma \times \Delta x) \times Y^2 / g \quad \textbf{(3-7)}$$

3.2 Mine haul road structural design

Haul road design, construction and maintenance management are critical to the performance and life of roads. The difference in applied loads, truck dimensions, traffic volumes, size of the tires used, construction material quality and availability and climatic conditions, together impact design life and road user cost considerations. These create differences for which designing and management of roads can be highly variable.

In truck based hauling systems, the mine haul road networks are critical and vital elements in the production process. Underperformance of roads impacts productivity and cost; up to millions of dollars, can be spent maintaining roads, repairing damaged truck frames and replacing tires. Productivity, equipment longevity and operations safety are all dependent on well designed, constructed and maintained roads (Thompson, 2011b).

Haul road cross-section

A haul road cross-section can be divided into four distinct layers, namely sub-grade, sub-base, base and surface or wearing courses. The sub-grade is the existing or excavated ground surface into which road fill is placed. The sub-base, base and surface are layers of fill of increasing quality that are successively placed above the sub-grade to form the fill.

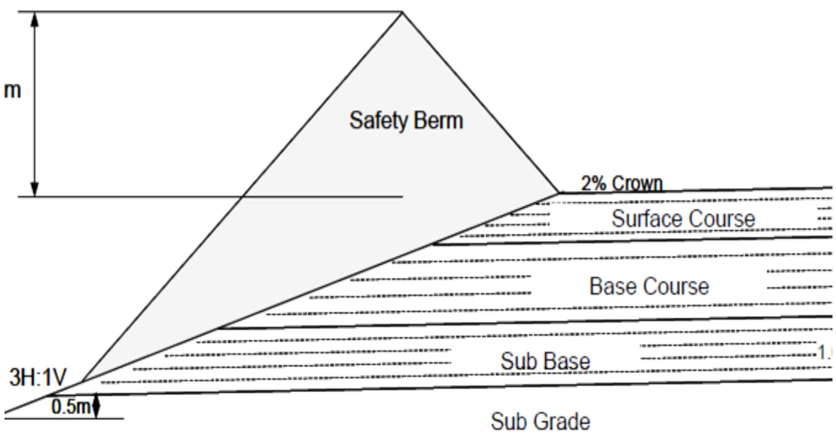


Figure 3-2: Typical haul road cross-section (Tannant & Regensburg, 2001)

S***ub-grade****:* Sub-grade can consist of native in-situ soil or rock, previously placed landfill or mine spoil. Where the sub-grade comprises hard, sound rock or dense, compact gravel, little or no fill may be necessary as haul trucks can travel on the sub-grade surface. At the other end of the spectrum, soft clays will require substantial quantities of fill to help spread the heavy wheel loads and prevent rutting, sinking or overall road deterioration.

Sub-base*:* Sub-base is the layer of a haul road between sub-grade and base of the road. It usually consists of compacted granular material, either cemented or untreated. Run of mine and coarse rocks are the general components of this layer. Apart from providing structural strength to the road, it serves many other purposes such as preventing intrusion of sub-grade soil into the base layer and vice-versa, minimizing effects of frost, accumulation of water in the road structure, and providing a working platform for construction equipment.

The sub-base distributes vehicle loads over an area large enough that the stresses can be borne by the natural, sub-grade material. The lower the bearing capacity of the ground, the thicker the sub-base must be.

Base: The layer of haul road directly beneath the surface layer of the road is called the base. If there is no sub-base then the base is laid directly over the sub-grade or roadbed. Usually higher quality treated or untreated material with suitable particle size distribution is used for construction of this layer. Specifications for base materials are generally considerably more stringent for strength, plasticity, and gradation than those for the sub-grade. The base is the main source of the structural strength of the road.

Surface (wearing course)*:* The uppermost layer of the haul road that comes directly in contact with tires is known as the surface (wearing) course or running layer. A haul road surface is generally constructed with fine gravel with closely controlled grading to avoid dust problems while maintaining proper binding characteristic of the material. Apart from providing a smooth riding surface, it also distributes the load over a larger area thus reducing stresses experienced by the base (Tannant & Regensburg, 2001)

This is the alignment of a haul road layers. Next stage in road design is determining thicknesses of these layers depending on sub-base strength, material properties and traffic volume.

The structural design

The structural design provides haul road 'strength' to carry the imposed loads over the design life without the need for excessive maintenance, necessitated by deformation of one or more layers of the road most often caused by soft, weak or wet in-situ materials below the road surface. Haul roads deteriorate with time due to interactive efforts of traffic load and specific in-situ material strength. Two approaches are commonly used for structural design. The California Bearing Ratio (CBR) method (Kaufman & Ault, 1977) has been widely applied to design mine haul roads in which untreated materials are used. When multilayer roads are considered in conjunction with a base layer of selected rock, a Mechanistic Approach is considered more appropriate (Thompson, 2011b). In both cases, an understanding of haul truck tire interactions is necessary.

CBR cover curve

The California Bearing Ratio (CBR) cover curve design method was developed in 1942 and Kaufman and Ault (1977) were among the first to recommend the use of the CBR method for the design of haul roads in surface mines. The approach characterizes the bearing capacity of a given soil as a ratio to the bearing capacity of a standard-crushed rock; the ratio of capacities being referred to as the CBR for the given soil. Empirical curves, known as CBR curves, relate the required fill thickness and applied wheel load to the CBR value. The technique is used for successive layers with the requirement that each successive layer should be of higher CBR than the preceding, and that the change in CBR should not be abrupt since the preceding layer acts as a compaction cover to the subsequent layer (Thompson, 2011b).

The United States Bureau of Mines (USBM, 1977) recommended accommodation of wheel loads up to 55-mt (300mt GVW) truck size which was later extended to accommodate ultra size trucks of up to 630mt GVW (Thompson, 2010). Figure 3-3 shows an updated version of the USBM CBR design charts appropriate for ultra class trucks, together with the approximate bearing capacities of various soil types defined by The Unified Soil Classification (USC) and American Association of State Highway Transportation Official's Systems (AASHTO).

Wheel loads for any haul truck can readily be computed from the manufacturer's specifications. It has been noted that haul trucks are frequently loaded above their rated weight capacity which should be taken into consideration for road design. By dividing the loaded vehicle weight over each axle by the number of tires on that axle, the maximum load for any wheel of the vehicle may be established. In every case, the highest wheel load should be used in design computations (Thompson, 2011b). Furthermore in evaluating distribution of wheel loads for a given time period of operation for a haul truck it is possible to evaluate a neglected mean load which may also be argumentative.

The CBR method is particularly useful for estimating the total cover thickness needed over the in-situ sub-grade material. A weaker sub-grade requires thicker layers of road construction material. This moves the truck tires higher away from the weak in-situ material, thus diminishing strains for a given material horizon to a level that can be tolerated by the sub-grade and lower successive lower layers.

Shortcomings of CBR method

Morgan (1994) and Thompson & Visser (1997a) criticized the CBR method of haul road design for the following considerations:

- The CBR method is based on Boussinesq's semi-infinite single layer theory, which assumes a constant elastic modulus for different materials in the pavement. Various layers of a mine haul road consist of different materials each with its own specific elastic moduli and other properties such as degree of compaction or moisture content

- The CBR method does not take into account the properties of the surface course material.

- The CBR method was originally designed for paved roads and surfaces for airfields. Therefore the method is less applicable for unpaved roads, especially haul roads which experience very different wheel geometries, poorer quality and construction materials (usually mine wastes).

- CBR empirical design curves were not developed for the high axle loads generated by large haul trucks as simple extrapolation of existing CBR design curves can lead to errors of under, or even over design.

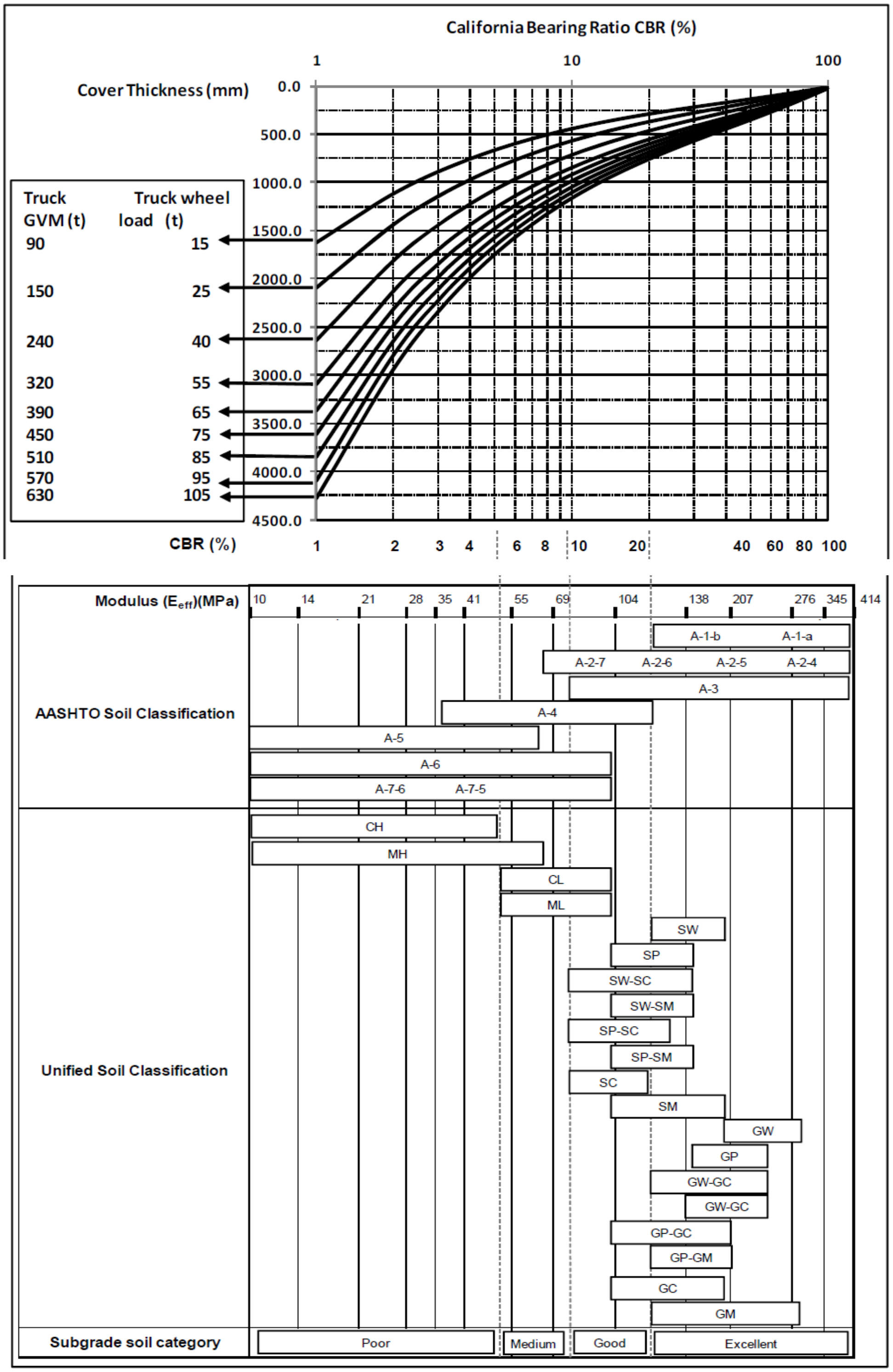


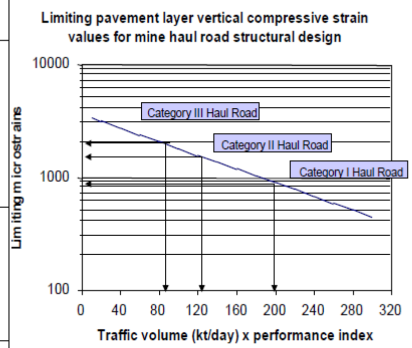
Figure 3-3: CBR cover curves for 90-630 metric ton GVM haul trucks and approximate bearing capacities of various soil types defined by UCS and AASHTO systems(after Thompson 2010)

Mechanistic design approach

A mechanistic approach supported by Thompson, (2011b) and others takes into account the differing properties in each layer and predicts their behaviour under applied load before construction by appropriate laboratory and in-situ testing. The road cross section is treated as a composite beam in determining the reaction of the structure to loading. A limit design criterion of vertical compressive strains of sub-grade and cumulative sub-layer below any given higher horizon of materials is used to assess the haul road under the specific load conditions, and hence determine the adequacy of a given road structural design.

This value of limiting strain is associated with the category of the road to be designed, truck size, traffic volume, performance required as a result of maintenance requirement over the life of the road and road operating life. The higher the wheel loads and traffic volumes together with longer required operating life and associated performance, the lower the required critical value as shown in figure 3-4. This data is used to calculate the thickness of the blasted rock to be placed on top of in-situ or sub-grade such that the road perform satisfactorily over its design life. Structural performance of the road is predominantly controlled by applied load, subgrade strength and pavement structural thickness.

Haul Road Category	Typical Description	Range of maximum permissible vertical compressive 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; • <5 years at >50kt/day) • <10 years at <50kt/day)	2000	2500



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

Figure 3-4: Typical haul road design categories and design data (after Thompson, 2011c)

Higher values of sub-grade critical strain cause permanent deformation to occur over many load repetitions, where deformation accumulates to cause rutting, the general shape of the road surface is lost. Riding quality deteriorates, serviceability reduces and rolling resistance increases which have direct impact on hauler availability, fuel consumption and emissions (Thompson, 2011c).

The mechanistic approach focuses on limiting load induced strain in progressively thicker sub-grade below a target horizon to below a set critical value. Based on field observations, the maximum vertical strain limits have been established to be 1500-2000 micro-strains for typical haul roads. Moreover, the stress level in any layer of a haul road cross-section should not exceed the bearing capacity of the material used in that layer. Values exceeding 2500 micro-strain are associated with unacceptable structural performance, except for light traffic and short term roads (Thompson & Visser, 1997b).

An empirical equation (3-8) for estimating the critical strain limit was developed by Knapton, (1988). This equation was developed for the heavy loading conditions found on docks at container ports. A modified version of the equation for haul roads shows a similar functional relationship between the critical strain limit and the design life of the road through traffic density:

$$E = 80{,}000 / N^{0.27} \qquad \textbf{(3-8)}$$

Where:

E = critical strain limit (micro-strain) and

N = number of load repetitions.

The stresses in individual layers below the surface layer can be calculated using stress models or the application of elastic theory. For example, the simplest assumption is that a tire creates a uniform circular load over an isotropic, homogeneous elastic half space as interpreted by Boussinesq. Although the assumption of homogeneity of individual layers in the haul road cross-section results in some error in estimation of the strain level in various layers, the assumption simplifies the problem for preliminary examination. This approach is still more acceptable than considering the entire haul road profile to be a singular equivalent material as was the previous practice of CBR approach.

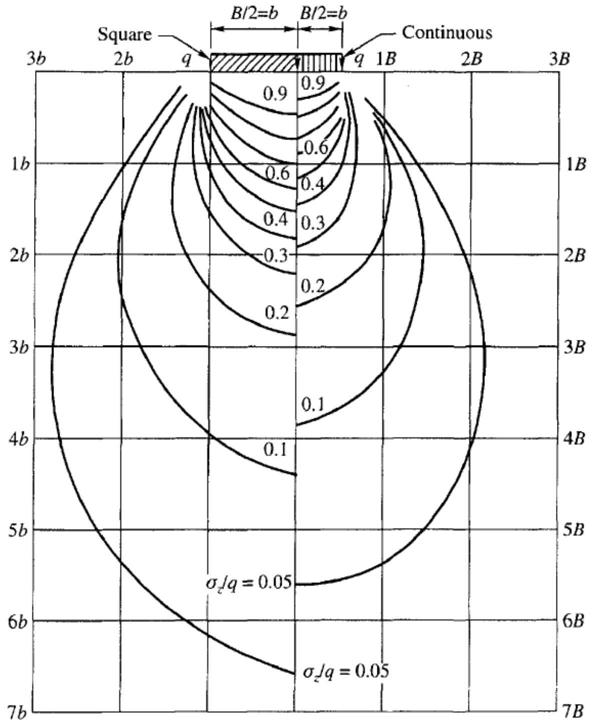


Figure 3-5: Boussinesq ground stress bulb (after Perloff, 1975).

The strains induced in a pavement are a function of the effective elastic (resilient) modulus values assigned to each layer in the structure. In order to facilitate a mechanistic design, some indication of applicable modulus values is required. Figure 3-3 gives recommended modulus value correlations USCS and AASHTO classification system. Equation 3-9 can also be used in conjunction with layer CBR values to determine modulus values (E_{eff}, MPa) (Thompson, 2011c)

$$E_{eff} = 17.63CBR^{0.46} \qquad \textbf{(3-9)}$$

3.3 **Functional design**

Functional design of the road is centered on the selection of a wearing course (or surfacing) material where the most suitable choice and application is required to minimize the rate of defect formation in road surface, which would otherwise compromise road safety and performance.

Typically natural gravel or crushed stone and gravel mixtures commensurate with safety, operational, environmental, and economic considerations are selected if readily available. In addition to their low rolling resistance and high coefficient of adhesion, their greatest advantage over other wearing course materials is that roadway surfaces can be constructed rapidly and at relatively low cost (Tannant & Regensburg, 2001). In the case of the Athabasca oil sand mines, gravel is at a premium and not readily available and so alternative material such as limestone crushed material or using chemical additions are currently being tested.

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

- Skid resistance
- Dustiness
- Loose material
- Corrugations
- Stoniness—loose
- Potholes
- Rutting
- Stoniness—fixed
- Cracks—slip, longitudinal, and crocodile. “Crocodile cracks” are cracks in a road caused by high plasticity/ high clay content material shrinking when drying. This is a well-known phrase among the pavement design fraternity.

By examining which wearing course material property parameters lead to these defects, a specification has been developed for wearing-course materials selection. The specifications are based on an assessment of wearing-course material shrinkage product (Sp) and grading coefficient (Gc), defined in Equations 3-10 and 3-11, (Thompson & Visser, 2006).

$$Sp = LS \times P_{425} \qquad \textbf{(3-10)}$$

$$Gc = \frac{(P_{265} - P_2) \times P_{475}}{100} \qquad \textbf{(3-11)}$$

Where;

LS = bar linear shrinkage

P_{425} = percent wearing course sample passing 0.425-mm sieve

P_{265} = percent wearing course sample passing 26.5-mm sieve

P_2 = percent wearing course sample passing 2-mm sieve

P_{475} = percent wearing course sample passing 4.75-mm sieve

If the three most critical haul road defects are considered, it appears that mine road user preference is for much reduced skid resistance and dust defects. This defines the focus point of the specifications to an area bounded by a grading coefficient of between 25 and 32 and a shrinkage product of between 95 and 130 in figure 3-6 where the overall and individual defects are minimized (Area 1). Extending this region to encompass poorer (but nevertheless operable) performance enables an additional area (Area 2) is defined (Thompson & Visser, 2006).

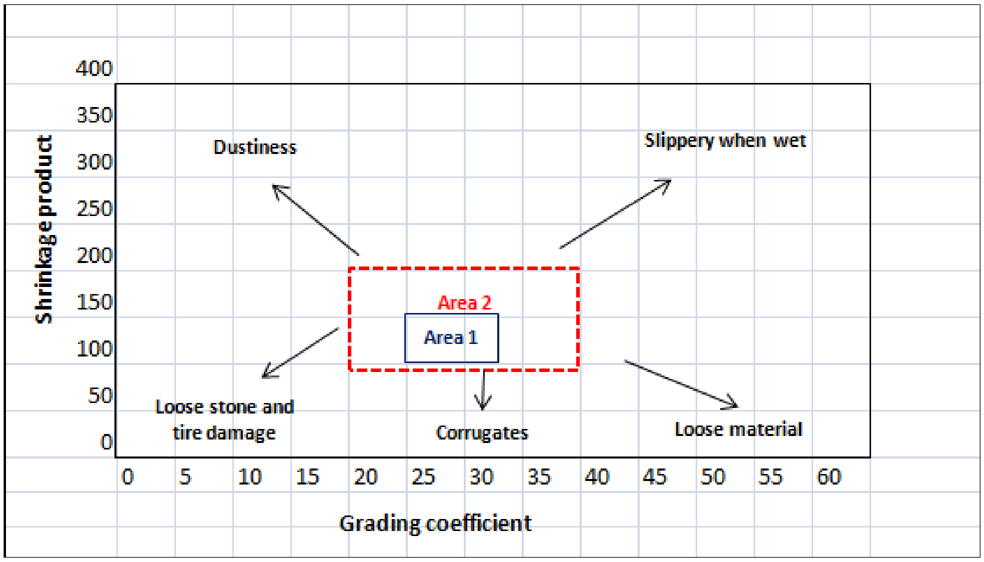


Figure 3-6: Haul road wearing course material selection (After Thompson and Visser 2006)

3.4 Rolling resistance

The condition of a haul road surface can have significant impact on the immediate and long-term performance of the road and haulage operating costs. Roughness and rolling resistance are two interrelated critical factors. Washboard, bumps and potholes generate impact forces that are transferred through the tires to the truck suspension, frame, and power train. The impact forces are roughly proportional to the gross vehicle weight above each wheel set multiplied by a 'g' level effect enhancing that value. Therefore, the road surface condition is especially important in larger trucks. Impact forces reduce tire life, increase fatigue in the suspension due to heat and trucks frame fatigue, resulting in increasing maintenance costs and shortening of truck life.

Rolling resistance change over time

The rolling resistance of a haul road is primarily related to the wearing course material used, its engineering properties, and the traffic frequency on the road. These dictate, to a large degree, the rate of increase in rolling resistance. "Road defects leading to rolling resistance can be minimized through careful selection of the wearing course, which will minimize, but not totally eliminate, rolling resistance increase over time," Thompson, (2011c). Wearing course properties and traffic volume are important parameters with regard to prediction of deterioration progression.

To estimate rolling resistance (RR) at a given point in time Thompson & Visser , (2000) established the relationship in equation 3-12 which estimates roughness defect score. It can be determined from an initial estimate of the minimum and maximum roughness defect scores (RDSMIN, RDSMAX), together with the rate of roughness defect score increase (RDSI). Rolling resistance at a point in time (D days after road maintenance) is then estimated from a minimum value (RRMIN) and the associated rate of increase.

The equations developed which are shown below may be used, together with the parameters and variables defined in the table 3-1.

$$RDS = RDSMIN = \left[\frac{RDSMAX - RDSMIN}{1 + \exp^{(RDSI)}} \right] \qquad \textbf{(3-12)}$$

Where;

$$RDSMIN = 31{,}1919 - 0{,}05354.SP - 0{,}0152.CBR \qquad \textbf{(3-12a)}$$

$$RDSMAX = 7{,}6415 + 0{,}4214.KT + 0{,}3133.GC + 0{,}4952.RDSMIN \qquad \textbf{(3-12b)}$$

$$RDSI=1{,}768+0{,}001.D(2{,}69.KT-72{,}75.PI -2{,}59.CBR \;\; 9{,}35.GC+1{,}67.SP) \qquad \textbf{(3-12c)}$$

And

$$RR = RRMIN + RDS.\exp^{(RRI)} \qquad \textbf{(3-12d)}$$

Where;

$$RRMIN=\exp^{(-1{,}8166+0{,}0028.V)} \qquad \textbf{(3-12 e)}$$

$$RRI = -6{,}068 -0{,}00385.RDS +0{,}0061.V \qquad \textbf{(3-12 f)}$$

Table 3-1: Parameters and variables for RR estimation

Parameter	**Description**
RDS	Roughness defect score
RDSMIN	Minimum roughness defect score immediately following last maintenance cycle

RDSMAX	Maximum roughness defect score
RDSI	Rate of roughness defect score increase
RR	Rolling resistance (N/kg)
RRMIN	Minimum rolling resistance at (RDS) = 0
RRI	Rate of increase in rolling resistance from RRMIN

Variable	Description
Vo	Vehicle speed (km/h)
D	Days since last road maintenance
KT	Average daily tonnage hauled (Kt)
PI	Plasticity index
CBR	100% Mod. California Bearing Ratio of wearing course material

3.5 Chapter conclusion

Road width depends on the width of a truck plus the extra width on a switchback; this means with larger trucks wider roads are required. Road gradients vary from 0% to 8% and on short distances can be higher. On soft underfoot when using larger trucks the grade of less than 6% is more favourable.

Haul road layer thicknesses are influenced by traffic loads, in-situ material properties, performance requirements and road operating life. The higher the wheel loads, traffic volume, higher performance requirement and longer operating life, the lower the limiting strain which necessitates additional road layer thickness.

Rate of rolling resistance increase is associated to wearing course material used and traffic frequency. Weaker material and higher traffic volumes result into faster rolling resistance deterioration rates.

4 FUEL CONSUMPTION AND EMISSIONS

Haul truck operations are a major contributor to overall surface mining equipment operating costs. Most mines use trucks as the means of primary haulage in North America (Kecojevic & Komljenovic, 2010). Among the primary costs associated with the use of trucks, fuel consumption is in line with tire costs, haul road construction and maintenance and equipment maintenance. A number of factors contribute to fuel consumption, major ones being; truck load, speed, engine power and road conditions.

4.1 Fuel consumption

The best way to determine fuel consumption is to obtain data from the actual mine operation. In the absence or limited data availability such data maybe estimated from equations and published data via the truck Original Equipment Manufacturer (OEM) which may be used for estimation purposes.

According Runge, (1998) and (Filas, 2002) an hourly fuel consumption FC (l/h) may be determined from equation 4-1:

$$FC = P \times 0.3 \times LF \qquad \textbf{(4-1)}$$

Where P is engine power (kW), 0.3 is a unit conversion factor (l/kWh) and LF is an engine load factor (the portion of full power required by the truck). Values for the truck engine load factors range from 0.18 to 0.50 (Runge, 1998) while Filas, (2002) states that engine load factors typically range between 0.25 and 0.75, depending on the equipment type and use level; the latter being more reflective of modern ultra-class haulers at the upper end of the scale.

A similar equation for fuel consumption was suggested by Hays, (1990):

$$FC = \frac{CSF \times P \times LF}{FD} \qquad \textbf{(4-2)}$$

Where, CSF is the engine specific fuel consumption at full power (0.21 – 0.27 kg/kWh) P is power (kW), LF is engine load factor and FD is the fuel density (0.85 kg/l for diesel). Hays recommends the following values for engine load factors: 25% (light: considerable idle, loaded hauls on favorable grades and good haulage roads); 35% (average: normal idle, loaded hauls on adverse grades and good haulage roads); and 50% (heavy: minimum idle, loaded hauls on steep adverse grades).

Liebherr developed a method to determine the truck fuel consumption per hour. According to this OEM, the fuel consumption rate is directly proportional to delivered power on different truck sizes (Boucom, 2008). Assuming the load factor of 100%, the relationship between fuel consumption and power was obtained as;

$$FC(LF100\%) = 0.2139P + 60 \tag{4-3}$$

Caterpillar also provides data on fuel consumption for its trucks by load factors. The load factors defined are categorised depending on gross vehicle weight, payload and road conditions.

The other approach to quantify fuel usage depending on hauler size was put forward by Leslie, (2000). He suggested that the fuel consumption per tonne may be decreased by moving to larger equipment supported by the data collected from Detroit Diesel Corporation (DDC) haul truck engines (Terex Unit Rig) shown in figure 4-1.

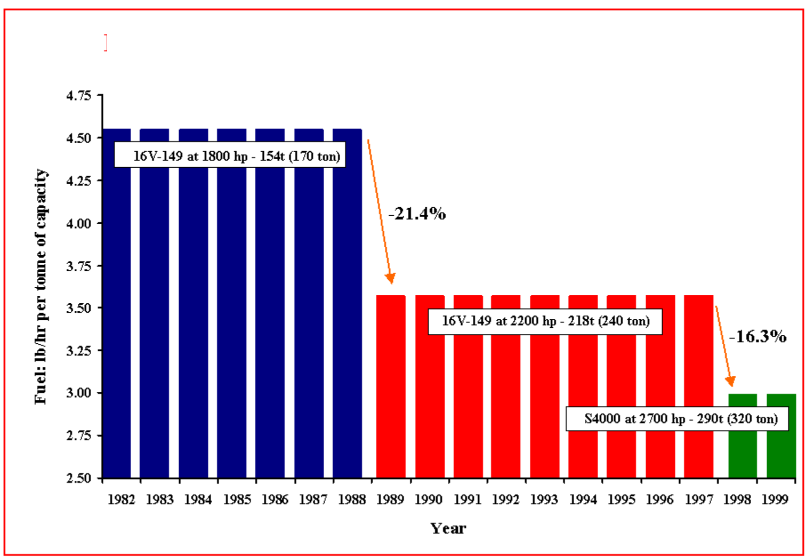


Figure 4-1: DDC Fuel consumption per ton of truck capacity (After Leslie, 2000)

4.2 Diesel emissions

One of the disadvantages of truck and shovel mining systems is the increase in diesel emissions. A large percentage of mining related emissions are attributed to mine hauler fleets as the result of fuel combustion. In the oil sands region of Northern Alberta a large percentage of regional NOx emissions is attributed to mine fleets (Singh, Rawling, & Unrau, 2008). Other research conducted on a surface coal mining operation in West Virginia show that a total of 966 tons of NOx per year was emitted in the mine. In this case haul trucks and blasting contributed to the total emission by 44.7% and 22.3%, respectively (Lashgari, 2013)

4.2.1 Diesel combustion

Diesel combustion consists of oxidizing hydrocarbon chains (C_xH_y) in an explosive reaction to form carbon dioxide (CO_2) and water (H_2O) in which the reaction is not 100% efficient and the constituents are not pure. The air used to supply the oxygen (O_2) contains about 80% nitrogen (N_2) and the diesel fuel contains a small percentage of sulphur (S). The result is that trace amounts of other chemicals are formed in the reaction as described on the equation below (After Leslie, 2000).

$C_xH_y(S_z) + (O_2 + N_2) \longrightarrow CO_2 + H_2O + (O_2 + N_2) + \{NOx + HC + OOC + C + CO + SOx\}$

Combustion Reaction $\longrightarrow$ Major Constituents + {Trace Constituents}

Of the major constituents of the reaction, CO_2 is a concern as a potential "greenhouse" gas and a theoretical contributor to "global warming". Since it is an integral part of the reaction, the way to reduce output is to increase the efficiency of the engine and reduce fuel consumption. CO_2 is produced at rate of approximately 2.73 kg/litre of fuel (Jaques, 1992), The production of SOx is directly related to the amount of sulphur in the diesel fuel. The other trace constituents are the result of incomplete combustion. Unburned hydrocarbons are the products of partial combustion account for the HC, OOC (oxidizable organic carbon), and free carbon (C) components of the trace constituents. Additional compounds of Nitrogen contribute to the formation of 'smog' after further reactions in the presence of sunlight (hʋ), and can pose health risks as concentrations rise.

The visible portion of PM, black smoke consists of is larger carbon particles that are formed under acceleration and heavy loading due to insufficient air or low combustion temperatures. Modern electronic engine controls can minimize the formation of black smoke such that it is rarely visible (Leslie, 2000).

NOx is also produced in the high temperature, high-pressure diesel fuel combustion chamber when there is excess oxygen available to combine with nitrogen during the reaction. Oxides of nitrogen can react in the atmosphere to form acidic compounds as well as promote low level ozone (O_3), a major component of smog. Ozone can be a lung irritant and can cause serious health effects and breathing difficulty in higher concentrations.

4.2.2 Engine development

Engine manufacturers have been driven by the need to reduce the operating costs of the engines they produce. This has been accomplished by designing engines that require less maintenance and burn less fuel. Even without a focussed effort, most emission component levels were in parallel reduced with this strategy. By producing engines that are more efficient, the manufacturers reduced products of incomplete combustion including CO, HC, and OOC, as well as CO_2 since less fuel was consumed. The only component of the emissions that did show any potential for increase was NOx, since its formation primarily occurs as temperatures rise in a combustion chamber (Leslie, 2000).

4.2.3 Diesel emission improvement

Over the years there has been improvement in engine efficiency. This evolution in engine technologies made it possible for bigger trucks to use fuel more efficiently and produce fewer emissions. Therefore the increase in size and engine efficiency result in lower fuel usage and fewer emissions for the same amount of work performed and make their use more cost effective.

Table 4-1 shows an example of Caterpillar data gathered by Leslie, (2000) from four different sized haul trucks that all use 3500 series engines that vary in configurations. It is evident that with increasing size, emissions decrease.

Table 4-1: CAT haul trucks emission data (After Leslie, 2000)

Caterpillar Data (98/10/30) ISO 8178; Type C1 8-Mode cycle data (weighted average)

CAT Machine: 777 (100 ton)
Engine: 3508 at a SCAC temp. of 56 degrees C.

Machine Model:	777C	777D	777D	777X
Engine Model:	EUI	B-Series	Tier I Reg.*	Tier II Reg.**
Rated Power (HP):	920	1000	1000	TBA
NOx (gram/HP-Hr):	10.06	7.48	6.90	4.80
CO (gram/HP-Hr):	1.65	0.53	8.50	2.60
HC (gram/HP-Hr):	0.28	0.24	1.00	N/A
PM (gram/HP-Hr):	0.13	0.14	0.40	0.15
***BSFC (gram/HP-Hr):	164.6	156.2	TBA	TBA
Maximum Payload (t):	86.2	91.0	91.0	91.0

CAT Machine: 785 (150 ton)
Engine: 3512 at a SCAC temp. of 56 degrees C.

Machine Model:	785B	785C	785C	785X
Engine Model:	EUI	B-Series	Tier I Reg.*	Tier II Reg.**
Rated Power (HP):	1380	1447	1447	TBA
NOx (gram/HP-Hr):	10.81	8.70	6.90	4.80
CO (gram/HP-Hr):	1.70	0.63	8.50	2.60
HC (gram/HP-Hr):	0.26	0.23	1.00	N/A
PM (gram/HP-Hr):	0.12	0.10	0.40	0.15
***BSFC (gram/HP-Hr):	155.9	151.8	TBA	TBA
Maximum Payload (t):	136.0	136.0	136.0	136.0

CAT Machine: 789 (195 ton)
Engine: 3516 at a SCAC temp. of 56 degrees C.

Machine Model:	789B	789C	789C	789X
Engine Model:	EUI	B-Series	Tier I Reg.*	Tier II Reg.**
Rated Power (HP):	1800	1904	1904	TBA
NOx (gram/HP-Hr):	10.85	9.61	6.90	4.80
CO (gram/HP-Hr):	1.04	0.55	8.50	2.60
HC (gram/HP-Hr):	0.28	0.25	1.00	N/A
PM (gram/HP-Hr):	0.14	0.08	0.40	0.15
***BSFC (gram/HP-Hr):	161.2	151.2	TBA	TBA
Maximum Payload (t):	177.0	177.0	177.0	177.0

CAT Machine: 793 (240 ton)
Engine: 3516 at a SCAC temp. of 65 degrees C.

Machine Model:	793B	793C	793C	793X
Engine Model:	EUI	B-Series	Tier I Reg.*	Tier II Reg.**
Rated Power (HP):	2160	2300	2315	TBA
NOx (gram/HP-Hr):	10.92	8.02	6.90	4.80
CO (gram/HP-Hr):	0.81	0.69	8.50	2.60
HC (gram/HP-Hr):	0.48	0.27	1.00	N/A
PM (gram/HP-Hr):	0.14	0.12	0.40	0.15
***BSFC (gram/HP-Hr):	160.6	160.9	TBA	TBA
Maximum Payload (t):	218.0	218.0	218.0	218.0

* Tier I and Tier II Regulation emission numbers are maximum permissible values. Actual CO, HC, PM values will be similar to B-series values.
** Tier II changes the convention by combining NOx and HC, therefore the Tier II value will represent NOx + HC.
*** BSFC is associated with rated point.

4.3 Chapter conclusion

One of the disadvantages of truck and shovel mining system is the increase in emissions produced from the fuel consumed by these trucks. The best way to determine the amount of fuel consumption and emissions is from actual field data but in absence can be estimated from equations and published data from OEMs.

Major concern around emissions is their contribution to environmental and health impacts. Regulations have been put forward to control the amount of emissions produced from off road equipment. Improvements have been seen with current engines manufactured for larger trucks whereby with increased engine efficiency, such that fuel consumption and emission per tonne are much less compared with smaller trucks.

5 ANALYSIS

5.1 Overview

Over the past century, open pits have attempted to increase their production rates and lower production costs by use of larger equipment. Pits and haul roads designed to accommodate small equipment are now evaluated for the opportunity to accommodate bigger ones. This has been possible to others and others not due to operating conditions. Evaluation of aspects affected is important when making decision to either purchase equipment for a new mine or transitioning to bigger size equipment on an already operating mine.

This study is focused on evaluating the impacts of increasing size of haul trucks to mine planning in term of road size and construction, rolling resistance increase, fuel usage and diesel emissions. The costs and benefits are evaluated considering the amount of material to be stripped off to accommodate the bigger size, road pavement construction requirements for each truck size and increase in rolling resistance as the function of traffic volume and material properties. Fuel consumption and associated emissions are also evaluated subject to increasing in truck size and total resistance (rolling + grade).

To accomplish the objective of the research, it is proposed to compare the three different truck sizes from the same manufacturer (Caterpillar) and analyse their application impacts. The trucks chosen are CAT 785C, CAT 793F and CAT 797F. Similar operating conditions and production requirements are assumed for comparison purposes.

5.2 Haul road geometric design for different truck sizes

The size of road varies depending on size of vehicle using that road. Changing in road size impacts stripping cost and pit slope angle as well. As an illustration, to evaluate the impact of changing hauler size to road width and stripping; an initial pit is designed to accommodate the 136t trucks (CAT 785C). The pit slope is 70˚, pit depth 100m and ramp gradient 8%. The transition is made to accommodate CAT 793F (227t) trucks and again in a further iteration later to CAT 797F (363t).

Table 5-1: Trucks specifications (Caterpillar, 2012)

Truck type	Width (m)	Length (m)	Empty weight (t)	Payload (t)	GVW (t)	Payload/ GWV ratio	Net Power (hp)	tire size
CAT 785C	6.28	11.02	102.15	136	249.48	0.57	1,348	33.00-R51
CAT 793F	8.3	13.70	163.29	227	390.09	0.58	2,478	40.00R57
CAT 797F	9.53	14.80	260.69	363	623.69	0.58	3,793	59/80R63

Effects of truck size on stripping and road construction

Table 5-1 illustrates the information for each truck model. Road width for each is determined from Equation 3-1 from which for two way traffic, road width should be 3.5 times width of the truck.

Radius of the switchback is calculated from equation 3-2 using the following parameters; super-elevation (e) 5%, coefficient of lateral friction tire-road (U_{min}) 20% (for dry compacted gravel) and vehicle speed (V_o) 30km/hr (down-hill). Distance along the switchback is assumed to be semi-circular and the area and volume of material to be stripped off calculated from equations 5-1 and 5-2. Results obtained on switchback stripping are as shown on table 5-2.

$$A = \pi R^2 \quad \textbf{(5-1)}$$

$$V = \frac{\pi R^2 L}{2 \sin \alpha} \quad \textbf{(5-2)}$$

Where; R = turning radius, L = height of the road and α = pit slope angle

Table 5-2: Switchback stripping requirement

Truck type	Road width on switchback (m)	Turning Radius (m)	Road length (m)	Incremental Stripping on switchback (10^6 m^3)
CAT 785C	29	150	471	
CAT 793	38	159	500	0.365
CAT 797F	45	166	521	0.368

Using equations 3-4 to 3-7, pit specifications given above and truck specifications in table 5-1, transitioning from one truck size to the other, the overall pit slope and volume of waste stripping is calculated as shown in the table 5-3. The designed widths are more than what is suggested in equation 3-1 and 3-1a due to an additional width for angle of repose of construction material (38˚) added to all truck sizes.

Table 5-3: Truck size effects on overall pit slope and incremental stripping

Truck type	Approx width (m)	3.5×width + repose (m)	Design width (m)	Increase in road width (m)	Pit slope angle (deg)	Incremental stripping ramp (10^6 m^3)	Incremental stripping switchback (10^6 m^3)	Total stripping (10^6 m^3)
CAT 785C	6.28	26.06	26		70			
CAT 793	8.30	33.963	34	8	61.5	0.49	0.37	0.86
CAT 797F	9.75	39.965	40	6	55.5	0.38	0.37	0.74

This gives the rough idea of how much waste must be stripped off to extend the road size with a change in equipment. When stripping cost per cubic metre is known, it can be determined if it is economical to go for higher capacity trucks including costs for other infrastructures such as crusher dump access, shop size, bay doors etc. Apart from the increasing stripping due to increased road size, pit bottoms need be big enough to allow safe operations of trucks and corresponding loading equipment. For that reason the stripping ratio will practically be much more than what is indicated above.

5.3 Haul road structural design

Haul road structural design is divided into two parts. The first part is determination of layers thicknesses depending on truck weights and type of construction material used. The second part is the final haul road design which includes estimation of the total volume of material for road construction from pit bottom to the exit.

Road layers design

To determine the effect of truck size on road layers design, the road was constructed for each of the 3 truck types. For comparison, the road was designed to haul same amount of material using each of the three truck options with the same construction materials used. The effect of the size on road construction is defined from the difference in pavement thickness for different trucks weights.

Material selection

The material selected for road construction are crushed rock for surface, pit-run sand and gravel for base layer, till, mine spoil for sub grade and in-situ rock being firm clay. The properties of selected materials are as shown in table 5-4 where, by knowing the CBR value resilient modulus can be determined using figure 3-3, or equation 3-9.

Table 5-4: Construction material properties

Layer	Typical material	CBR (%)	Resilient modulus, MPa
Surface	Crushed rock	95	330
Base	Pitrun, sand & gravel	60	245
Sub-base	Till, mine spoil	25	130
Sub-grade	Firm clay	4	40

Critical strain

The roads were designed to haul 40Mt per year for five years using one truck option from the three different truck sizes. The truck cycle time regardless the size is set as 30mins and the trucks availability and utilization respectively 90%. Total cycle times per year per truck and number of trucks needed to achieve production were determined as follows;

Table 5-5: Cycle time calculations

production/day	109589.04t
production/year	40000000t
production in 5year	200000000t
cycle time	30mins
Availability	0.9
Utilization	0.9
cycles/year/truck	14191

Note:

$$production / day = \frac{total \ \ production \ \ per \ \ year}{\# of \ \ days \ \ per \ \ year}$$

$$(cycles / year) / truck = \frac{days \ \ per \ \ year \times hours \ \ per \ \ day \times \min utes \ \ per \ \ hour \times A \times U}{cycle \ \ time}$$

$$number \ \ of \ \ units = \frac{production \ \ per \ \ year}{truck \ \ payload \times cycle \ \ time / year}$$

Critical strains for trucks were calculated from equation 3-8

Table 5-6: Critical strain estimation.

truck type	20% overload	GVW (overload)	number of units	cycles/day	kt/day	**critical strain**
CAT 785C	163.2	265.35	17	672	178	**1506**
CAT 793F	272.16	435.45	10	403	175	**1730**
CAT 797F	435.6	696.29	6	252	175	**1964**

Contact stress estimation

Thompson, 2011b suggests that haul trucks are frequently loaded above their rated weight capacity and the maximum load should be used in road design. The fact is verified by the data collected from an oil sand field operations using 363t truck (CAT 797B). Tire loads were measured from all four tire positions for 7 hours. The obtained results are as shown on figure 5-1.

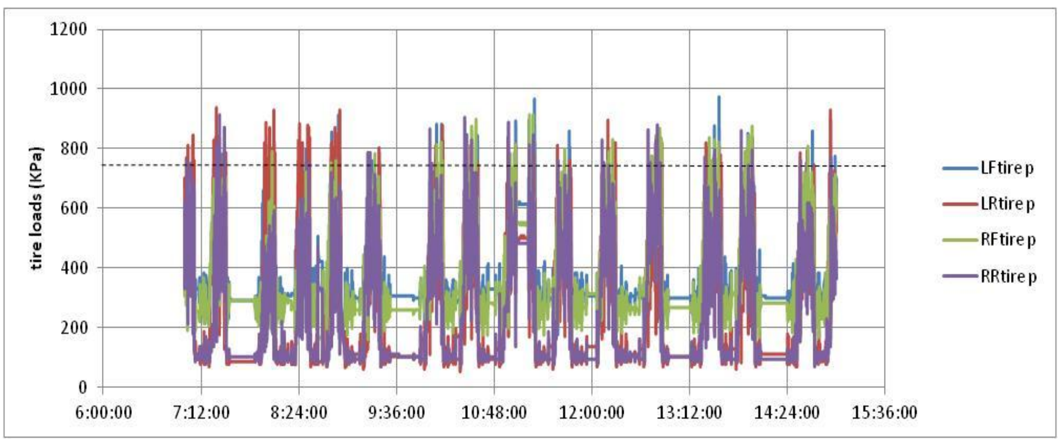


Figure 5-1: Tire loads in field operation

From figure 5-1; peak loads are approximately 750KPa. Normally for 100% payload, tire loads on CAT 797B would be around 675KPa. Being 750KPa proves that trucks may usually be (20%) overloaded and therefore tire load estimations are performed considering 20% overload.

Contact stress (tire load) is influenced by the truck tare weight, payload and tire footprint area. Estimations for contact stress for each truck type are as shown on table 5-7 below.

Table 5-7: Contact stress estimation

Truck type	CAT 785C	CAT 793F	CAT 797F
Tare weight, t	102.15	163.29	260.69
Payload (120%), t	163.20	272.16	435.60
GVW(Tare +120%P), t	265.35	435.45	696.29
Tire size	33.00-R51	40.00R57	59/80R63
Total load per tire, t	44.23	72.58	116.05
Footprint area, A	0.83	1.14	1.51
Equivalent tire width (b)	0.91	1.07	1.23
Stress exerted, σ (MPa)	**522.71**	**624.53**	**753.93**

Note:

1. Tire strain, δ = 7% (0.07) under normal1g loading (Sharma, 2009).
2. Footprint area, $A=1.35\delta\phi$ (experimental relation after Sharma, 2009)
3. Equivalent tire width, $b=\sqrt{A}$ (Joseph, 2002)
4. Contact stress = Total load per tire / Footprint area

The weight used in this case, was based on a truck considered to be static. However this might not be the case in dynamic conditions where operating force (weight) is amplified during motion. The weight distribution in strut locations differs.

For example; in static conditions ($V_o=0$) weight can be calculated by;

$$W=F=mg \qquad \text{(i)}$$

The mass m, contributing to each strut of the unit does not change and therefore the change is caused by variation in acceleration (a), enhancing or reducing 'g' at each strut location. Flexure in the frame give rise to the different values of 'a' which is in turn influenced by ground conditions (Joseph, 2003). This variation 'a' causes rack motion which varies weight at each tire set by F';

$$F'=m\,(g+a). \qquad \text{(ii)}$$

If a=g; then the weight reported on such particular strut will be F'=2F

Road structural design

Figure 5-2 presents a flow chart summary of the road design method based on resilient moduli of various layers in the road cross section. The method is based on the criteria that the vertical strain at any point in haul road should be less than a critical strain limit. The critical strain limit is dependent on the traffic density and design life of haul road.

Flowchart

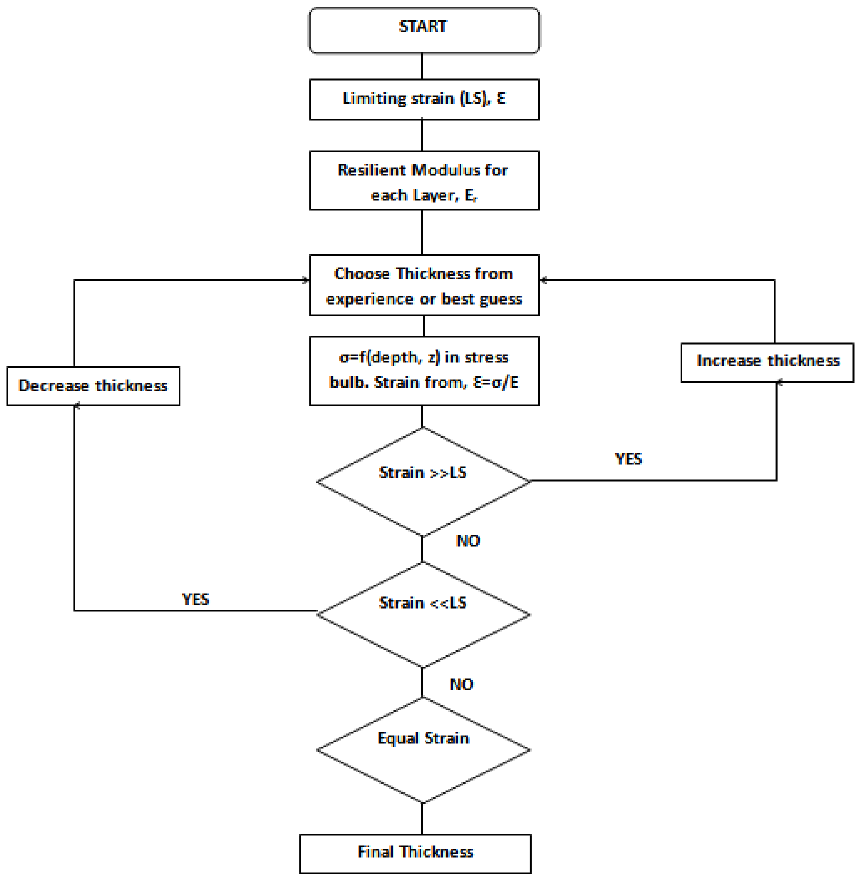


Figure 5-2: Steps for haul road pavement design (after Tannant & Regensburg, 2001)

For longer operating road life and performance, the pavement design should ensure that the induced strain does not exceed the critical strain. Using the

Boussinesq ground stress analysis model in figure 3-5 (used along with table A 1 in appendix) which describes by layers the variation of stress with increasing depth and the critical strains in table 5-6, pavement layer thickness for each truck type were obtained as shown in table 5-8. The difference in layers thicknesses for trucks is shown in table 5.9.

Table 5-8: Road layers thicknesses

	Cat 785C		Cat 793F		Cat 979F	
Layer	Total fill cover (m)	Layer thickness (m)	Total fill cover(m)	Layer thickness (m)	Total fill cover (m)	Layer thickness (m)
Surface		0.81		1.01		1.25
Base	0.81	0.72	1.01	0.84	1.25	0.97
Sub-base	1.53	1.68	1.85	2.00	2.22	2.34
Sub-grade	3.20		3.85		4.56	

Table 5-9: Road layers thicknesses difference in metres

	Cat793F/ Cat 785C	Cat 797F/ Cat 793F	Cat 797F/ Cat 785C
Surface	0.20	0.24	0.44
Base	0.13	0.13	0.26
Sub-base	0.32	0.34	0.66

A sample calculation on how layer thicknesses were obtained is described in appendix A.

Discussion on pavement layer thickness

Regardless of number of cycles, pavement layer thickness is impacted by weight of the truck. Figure 5-3 shows how the layer thickness is influenced by truck weight. The total pavement thickness increase at an average of 58% transitioning from CAT785 to CAT793F, 39% from CAT793F to CAT 797F and 120% from CAT785 to CAT797F. The individual increase in layer thicknesses is as shown on Table 5-10.

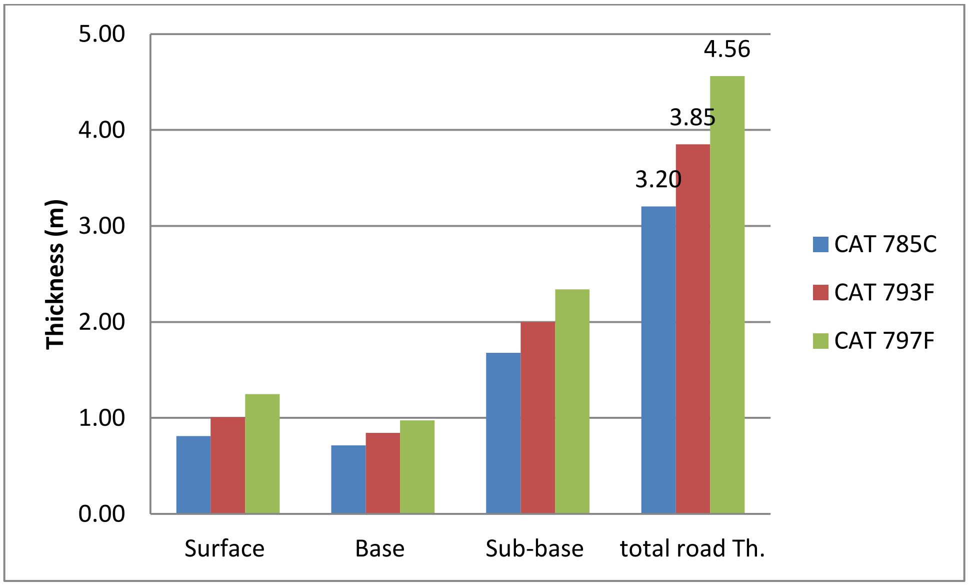


Figure 5-3: Road layers thicknesses for trucks

Table 5-10: Percentage increase in layer thickness due to truck weight

Layer	CAT 973F/785C	CAT 797F/793F	CAT 797F/785C
Surface	24%	24%	54%
Base	18%	15%	36%
Sub-base	19%	17%	39%
Average	**20%**	**19%**	**43%**

Construction material requirement

Consider a road to be constructed in a pit described in section 5.2. The road is constructed from pit bottom raising 100m elevation to the pit exit with ramp grade of 8% including one switchback. The total distance that could be constructed on ramp is 1.25km, with varying switchback distances depending on the turning radii of the trucks. Using equation 3-2 and assuming the travelling speed of 30km/hr (down-hill) for each truck type, road lengths on switchback are calculated as in Table 5-11.

Table 5-11: Road distances on switchback for different truck sizes

	CAT 785C	CAT 793F	CAT 797F
Surface , m	0.81	1.01	1.25
Base, m	0.72	0.84	0.97
Sub-base, m	1.68	2.00	2.34
road width, m	25	33	39
Switchback length , m	**471**	**500**	**521**
Turning Radius, m	150	159	166

Volume of road construction materials depends on the width of road section to be constructed and layers thicknesses. Road width is 3.5 times the size of the largest vehicle on ramp and 4 times the width on switchbacks. The road has a gradient of 8% on ramp and no grade on switchback. Volume of material required on road layers construction on each truck type is shown in Figure 5-4.

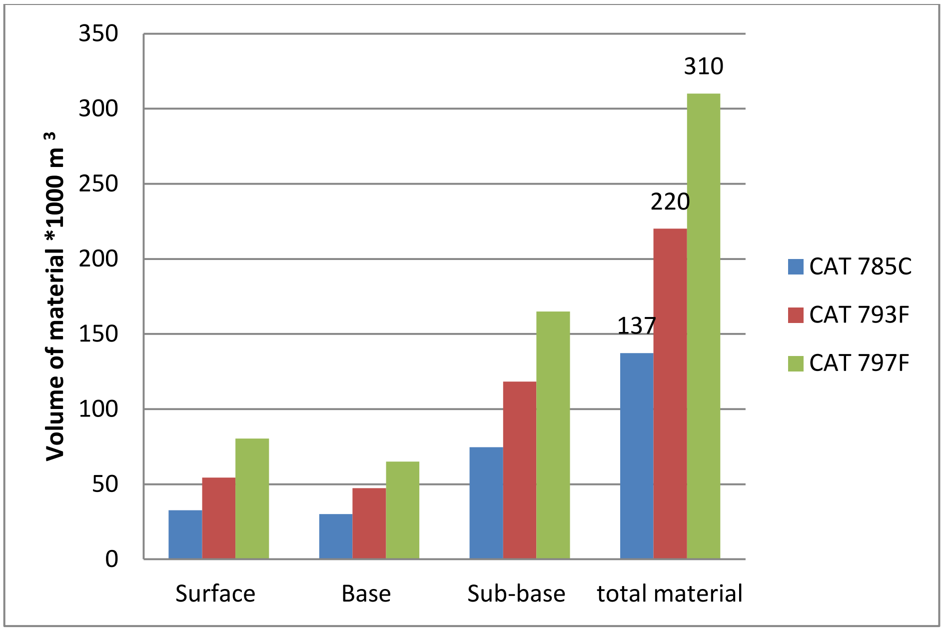


Figure 5-4: Construction materials requirement

Table 5-12: Percentage increase in road construction material

Layer	CAT 793F/785C	CAT 797F/793F	CAT 797F/785C
Surface	67%	48%	146%
Base	58%	37%	117%
Sub-base	58%	39%	121%
Average	**61%**	**41%**	**128%**

Indicated in Figure 5-4 above are the construction material requirements for an in-pit haul road only. Extensions to waste dump and/or crusher/stockpiles as the destinations for the mined rock need also to be constructed. The distance varies depending on their location and therefore construction materials illustrated above may likely go higher. The costs of construction materials may vary from one operation to another depending on the possibility of preparing these materials on-site. When deciding on truck size, considerations of road construction materials need to be also done to account for the overall cost of increasing truck size in an operation.

5.4 Rolling resistance

The rolling resistance is related to the wearing course material, material engineering properties and the traffic frequency on the road which dictates the rate of its increase. To estimate rolling resistance (RR) at a given point in time, the approach suggested by Thompson & Visser (2000) of estimating the roughness defect score (RDS) described in equation 3-12 was used. The parameters used for estimation are;

Vo 20km/hr (uphill)

D 12 days

KT calculated for each truck type

PI 4.64 (for A-1-a in AASHTO in figure 3-3)

CBR 95% (for wearing course material)

SP 112.5 (for category 2 roads)

GC 28.5 (for category 2 roads)

Note: Category 2 roads are semi-permanent roads with medium to high traffic volume. The elastic strain ranges from 1500 to 2000 micro-strain and traffic volume less than 100Kt/day (Thompson, 2011c).

Rolling resistance estimation

Given that the cycles per year per truck is 14191 from table 5-5; the cycles per day per truck is 39. For the three truck sizes, the traffic volume is estimated as shown in table 5-13.

Table 5-13: Traffic volume estimation

	CAT 797F	CAT 793F	CAT 785C
# units	6	10	17
Total trips/day	252	403	671
kt/day	**58**	**58**	**59**

Using the approach described in equation 3-12 rate of increase of rolling resistance for three truck sizes may be estimated. Rolling resistance (%) estimates for the first day of operation after maintenance is shown in table 5-14.

Table 5-14: rolling resistance estimation at day 1(after Thompson 2000)

	CAT 797F	CAT 793F	CAT 785C
RDSMIN	23.72		
RDSMAX	52.93	52.95	53.35
RDSI	1.26	1.26	1.27
RDS	30.16	30.17	30.24
RRMIN	0.17		
RRI	-6.06	-6.06	-6.06
RR(N/Kg)	0.24	0.24	0.24
RR %	2.38	2.38	2.38

The estimated rolling resistance increase rate for 12 days of operation are shown in figure 5-5.

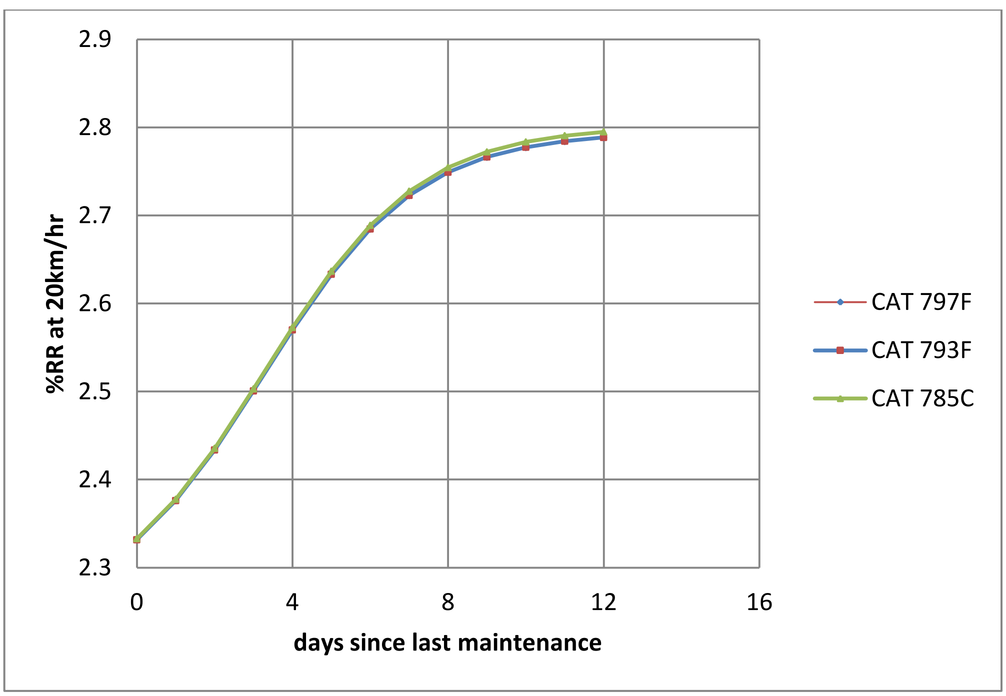


Figure 5-5: Trucks rolling resistance progression in 12 days

Rolling resistance discussion

The rate of increase in rolling resistance is basically the same regardless of truck size. The average difference in rolling resistance between three truck sizes used for 12 days is approximately 0.004% per day which is relatively small. Estimations of rolling resistance increase per day for the three truck sizes are shown on appendix B 2.

5.5 Section conclusion

The size of road varies with the size of trucks using the road. With larger trucks wider roads are required, which necessitates more stripping. Pit slopes are affected by the size of roads; with wider roads pit slopes decreases resulting in laying back pit walls as pit size increases.

Road layer thickness is influenced by the construction materials used, applied loads, performance level and required road life. If all other factors remain the same, regardless of load repetitions, road layer thickness is most influenced by truck load. The amount of road construction material required is a function of the road layer thickness and road width. With larger trucks, construction material requirements are much higher compared to smaller units.

When it comes to rolling resistance, the rate of increase is influenced by the surface wearing course material used and traffic volume. Using crushed stone as a wearing course material, the rate of increase in rolling resistance was observed to be the same regardless of truck size. This is due to ground bearing pressure for the tires being the same regardless of truck size. This in turn is an affect due to rubber properties of the tire being the same for any truck size and so there is a constant bearing pressure for a truck tire due to its material composition.

5.6 **Fuel consumption and diesel emissions**

Material haulage using trucks and shovel are of the leading mining costs. Haulage cost using trucks is associated to road construction and maintenance, fuel, tires and truck maintenance. This chapter focuses only on fuel consumption and emissions analysing how the size of a hauler influences its fuel consumption and thus the emissions.

5.6.1 Fuel consumption

Different studies have shown that with increasing size of trucks, the fuel consumption has decreased and therefore for the same work, bigger trucks consume less fuel than smaller ones. For analysis purposes two approaches are used from data collected from two different truck engines manufacturers.

The first approach uses the data collected by Leslie, (2000 refer figure 4-1) from DDC engines. From the data, relationship between fuel consumption per ton capacity was established as shown in figure 5-6.

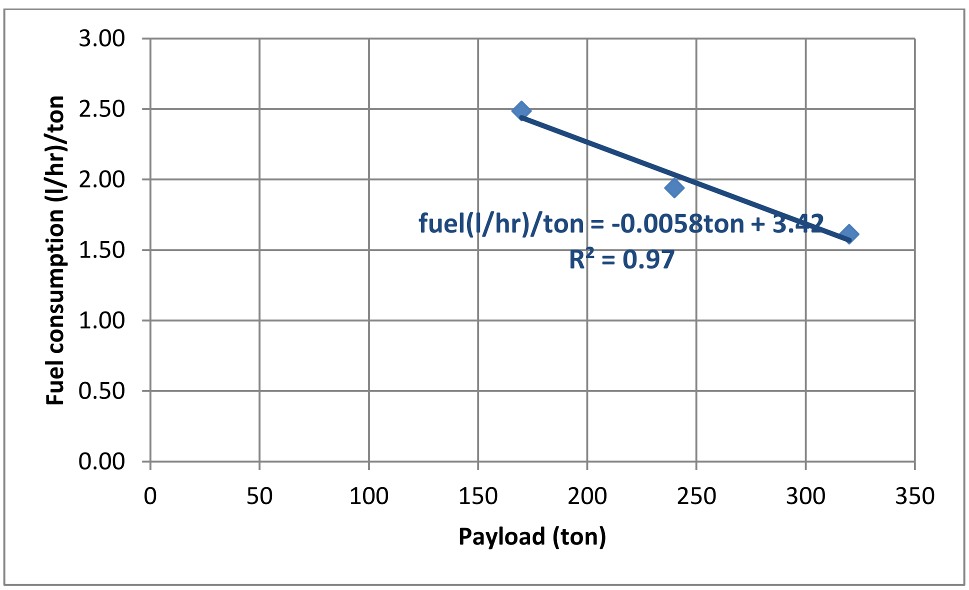


Figure 5-6: Relationship between DDC engines fuel consumption per ton and payload

A High regression value of R^2= 0.996 indicates a strong linear correlation between truck size and fuel consumption per ton for DDC engines.

The relationship between fuel consumption per hour and payload shows that with increasing size the fuel consumption increases to 300 ton trucks and decreases in higher tonnage trucks ranges (320ton and 400ton) as shown in figure 5-7. This is due to the improvement in "tier" engine efficiency with higher model engines in moving from tier 2 to tier 3 and beyond engines.

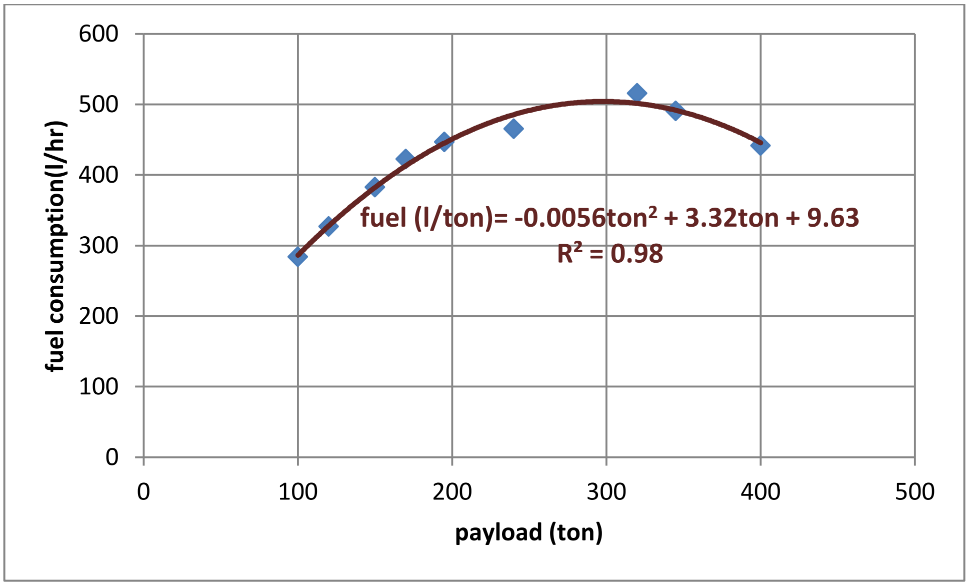


Figure 5-7: Relationship between DDC fuel consumption and payload

Another approach developed to determine fuel consumption was established from Liebherr (for MTU and Cummins engines). Using the relationship between fuel consumption (l/hr) and power (kW) via equation 4-3, a relationship between fuel consumption (lb/hr)/t and truck size (payload, ton) was obtained. This also showed that; with increasing truck size, fuel consumption per ton decreases.

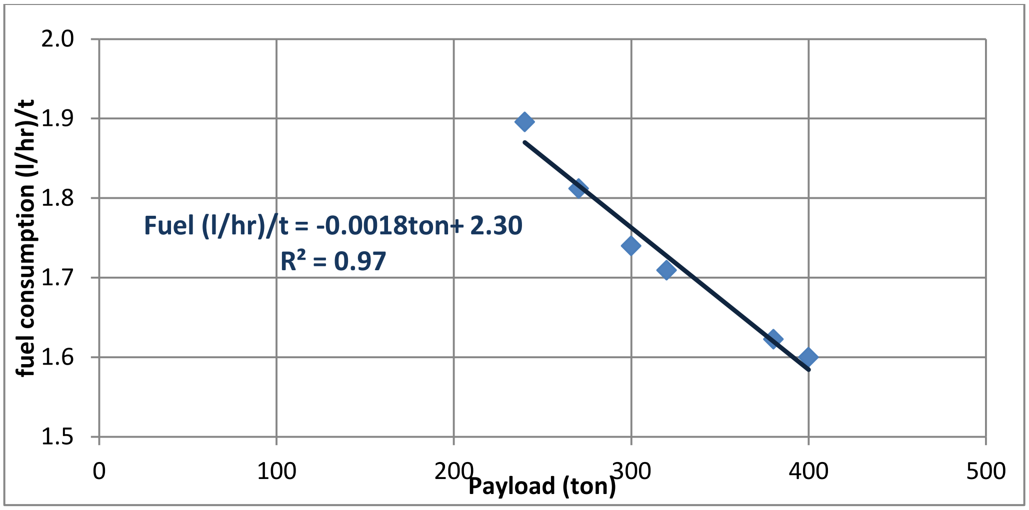


Figure 5-8: Relationship between Liebherr engines fuel consumption per ton and payload

Comparing with the first approach, the Liebherr engines indicate that fuel consumption per hour (lb/hr) increases with increasing truck capacity.

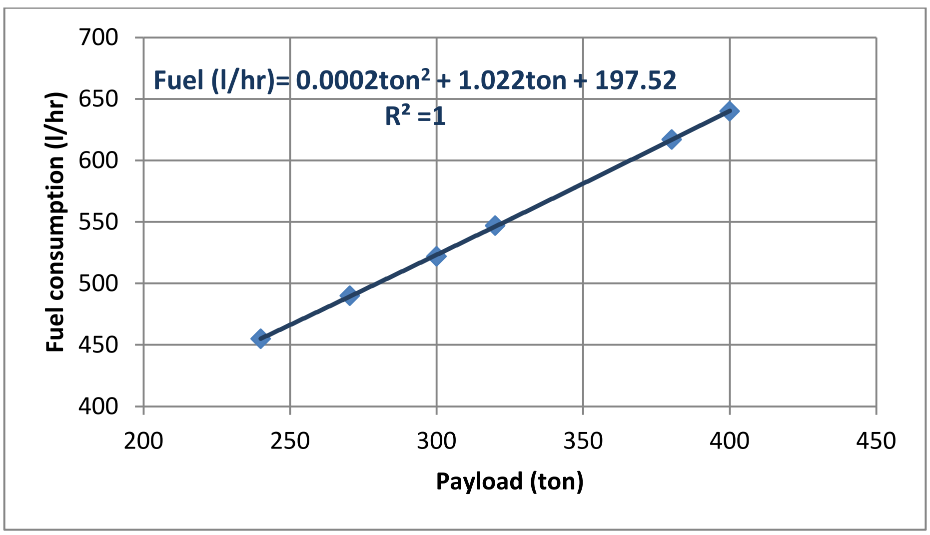


Figure 5-9: Relationship between Liebherr engines hourly Fuel consumption and payload

Note: The decision to use payload instead on GVW is made based on the fact that mine operators are more interested on how much fuel is used to move a certain amount of material.

5.6.2 Diesel emissions

Diesel engines are one of the major sources of air pollution particularly emissions of nitrogen oxides NOx, hydrocarbons (HC), Carbon monoxide (CO) and particulate matter (PM). These are major targets for regulation for their contribution to serious adverse health and environmental effects and they can be controlled (EPA, 2005).

Emissions are a function of engine efficiency and fuel consumption. Engine control strategies, including combustion optimization, better fuel control, exhaust gas recirculation, improved charge air characteristics and after treatment devices are used to control emissions. Diesel emissions have been improved this way to correspond to tier regulations as shown in figure 5-10.

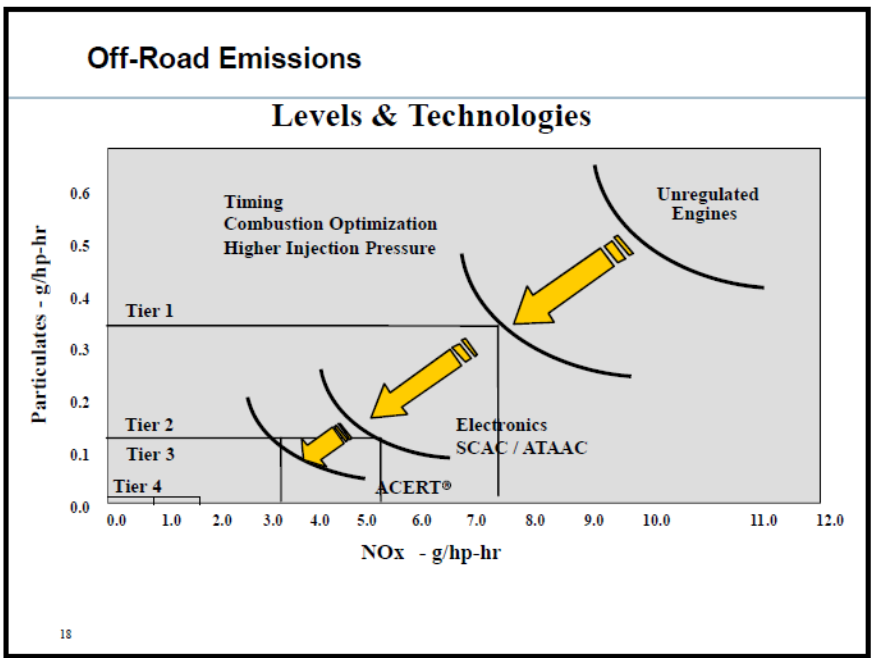


Figure 5-10: Emission control in tier engines (Caterpillar, 2008).

Using Leslie, (2000) data and some field data collected by Joseph (between 2000 and 2003 in oil sands operations) in table 5-15, some relationships between fuel consumption and emissions were developed as shown in figure 5-11 to 5-13.

Table 5-15: Fuel consumption and emissions data

hauler ton	fuel (lb/hr)/t	fuel (lb/hr)	hp	NOx (g/hp-hr)	CO (g/hp-hr)	HC (g/hp-hr)	PM (g/hp-hr)	NOx (g/hr)	PM (g/hr)
100	5.201	520.1	945	NA	NA	NA	NA	NA	NA
120	4.989	598.68	1600	NA	NA	NA	NA	NA	NA
150	4.671	700.65	1348	NA	NA	NA	NA	NA	NA
170	4.55	773.5	1800	NA	NA	NA	NA	NA	NA
195	4.194	817.83	1771	NA	NA	NA	NA	NA	NA
240	3.55	852	2337	4.8	2.6	4.8	0.15	11217.6	350.55
320	2.95	944	2700	2.3	0.697	2	0.1	6210	270
345	2.604	898.38	3188	1	0.7	0.5	0.075	3188	239.1
400	2.021	808.4	3793	0.5	0.5	0.5	0.025	1896.5	94.825

The relationships between fuel consumption and NOx & HC emissions are virtually parallel. High R^2 values indicate a strong linear correlation between fuel consumption and emissions as illustrated in figure 5-11.

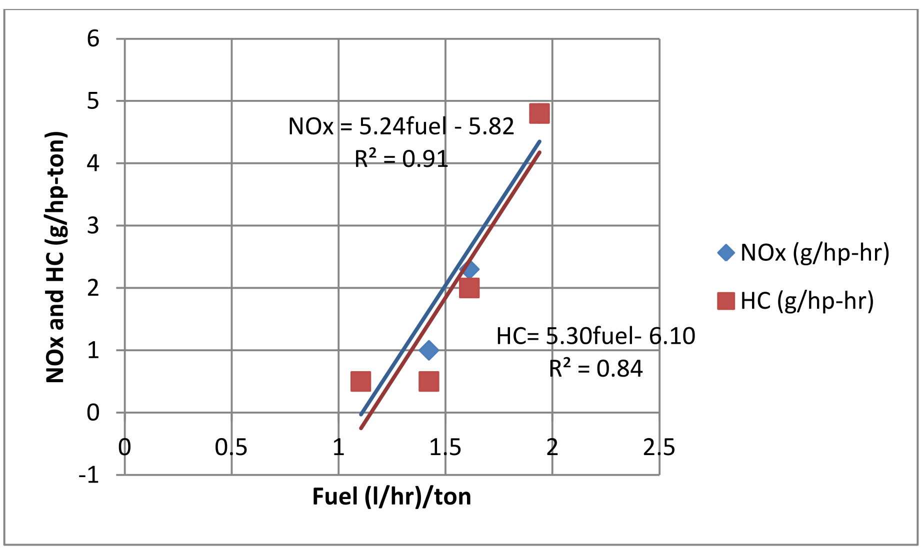


Figure 5-11: Relationship between fuel consumption with NOx and HC emissions.

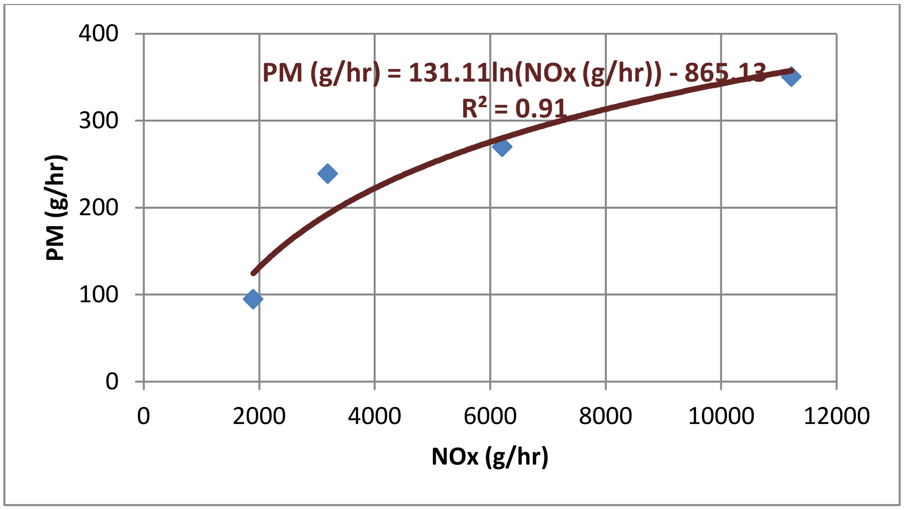


Figure 5-12: Relationship between NOx and PM

Relationship between NOx emissions and fuel consumption is logarithmic with $R^2 = 0.93$

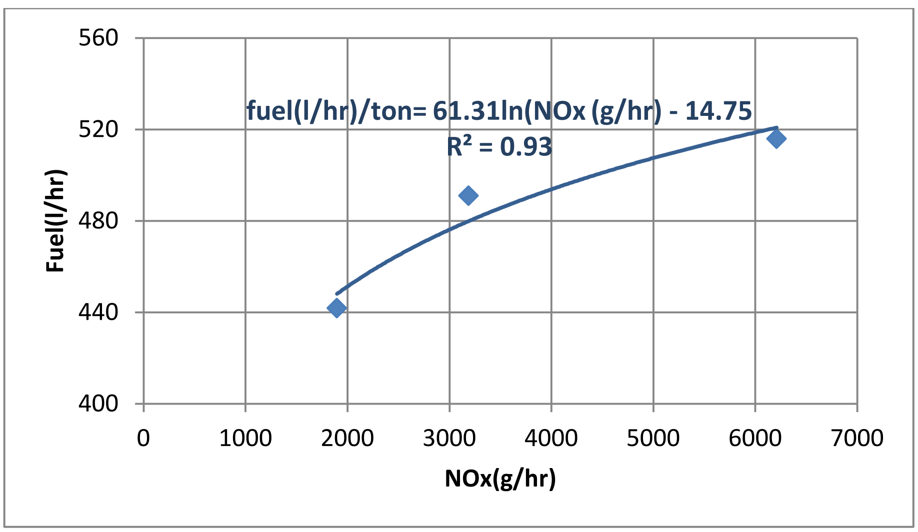


Figure 5-13: Relationship between NOx emissions and fuel consumption

Some research has been conducted specifically to determine diesel emissions in field operations. One report was generated by Golders Associates in the Athabasca oil sands region assessing emissions for mobile equipment (Singh, Rawling, & Unrau, 2008). The approach took into consideration equipment size, actual operating conditions and operating modes. An emission model known as GAME (Golder Associates Mining Emissions) was developed out of this work.

The 750 horsepower engine used was assumed to be used for an 80 ton capacity truck. From the data obtained, the relationships in figure 5-14 were established;

Table 5-16: NOx and CO emissions (After Rawlings and Unrau, 2008)

time (hrs)	**Grade (%)**	**RR % estimate**	**TR%**	**NOx (g)**	**CO (g)**	**NOx g/hr**	**CO g/hr**
0.2	0	12.6	12.6	97.68	24.64		
0.08	0	12.6	12.6	102.34	62.00	1279.25	775.00
0.07	3	11.4	14.4	113.01	65.92	1614.43	941.71
0.32	0	6.5	6.5	279.10	169.10	872.19	528.44
0.05	5	8.8	13.8	103.91	61.48	2078.20	1229.60
0.1	0	4.5	4.5	40.18	24.56	401.80	245.60
0.07	0	9.5	9.5	32.75	8.06		
0.2	0	9.5	9.5	194.35	101.52		

Relationships between NOx and CO emissions to total (grade + rolling) resistance were obtained with R^2 values of 0.87, where the relationships were suggested to be exponential.

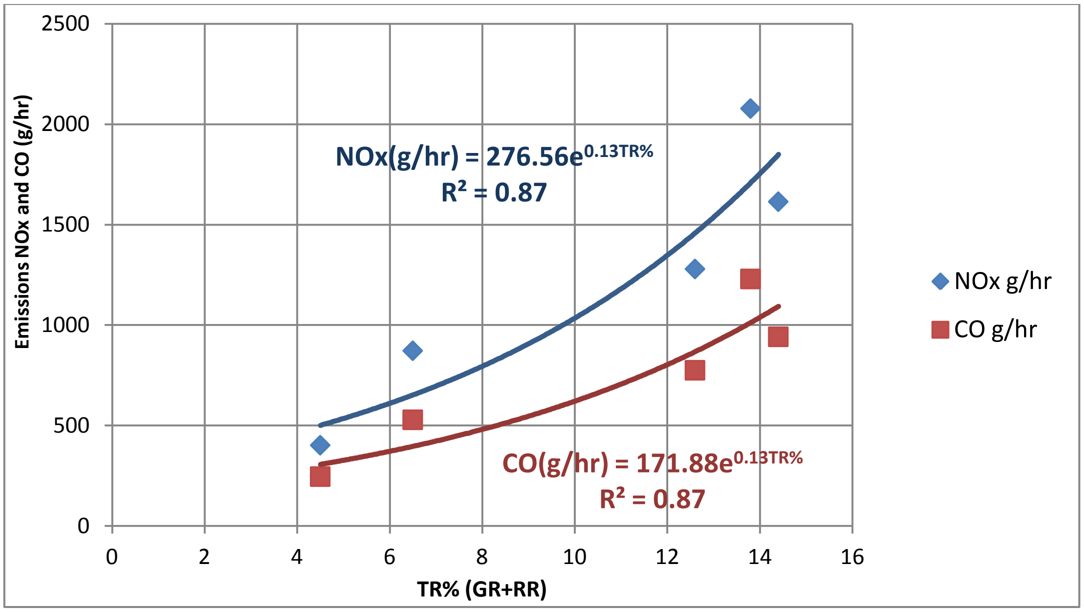


Figure 5-14: Relationship between NOx and CO emission and total resistance

The effect of size and total resistance to fuel consumption and emissions

From the NOx and CO relationships in figure 5-14 and the relationships obtained in figures 5-7, 5-11, 5-12 and 5-13, the comparison between 3 trucks sizes with capacities of 150 ton, 240 ton and 400 ton (assumed to be CAT785C, CAT793F and CAT797F) on fuel consumption and diesel emissions were made. The aim was to determine how fuel consumption and emissions vary with truck size including the impact of increasing rolling and grade resistance on each.

The fuel consumption and total resistance relationship was deduced from the relationships between fuel consumption and NOx emissions in figure 5-13 and relationship between NOx emissions and total resistance in figure 5-14.

The increase in total resistance increases fuel consumption per ton of hauler capacity. The effect was higher on smaller trucks compared to larger trucks. Figure 5-15 shows the increase in fuel consumption was 0.09(l/hr)/ton for

CAT785C, 0.07(l/hr)/ton for CAT793F and 0.04(l/hr)/ton for CAT797F haulers models per 1% increase in total resistance.

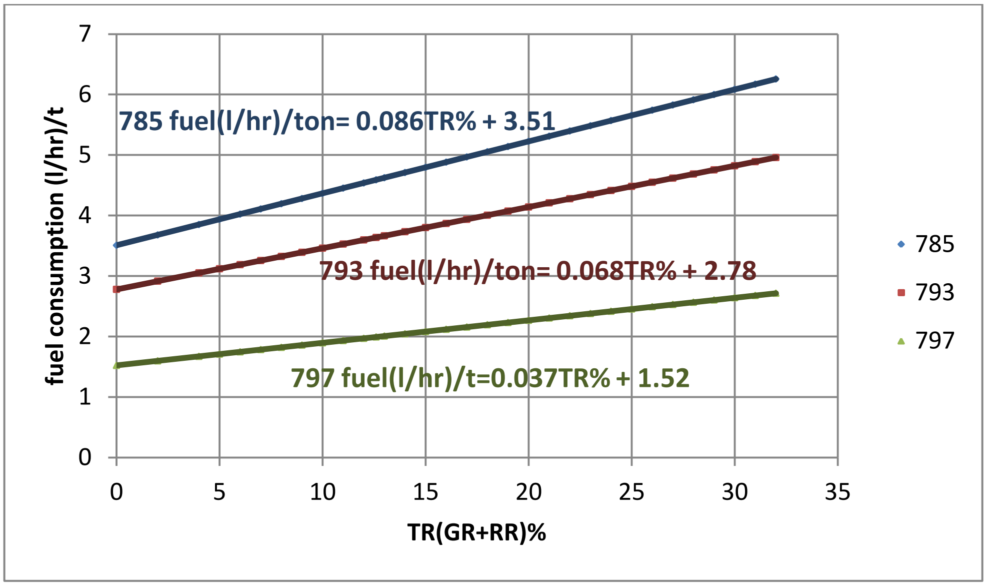


Figure 5-15: Relationship between TR and fuel consumption per ton

In most cases the grade resistance does not change; it is dependent on the ramp gradient. Rolling resistance is variable depending on surface material selection and maintenance frequency. From the above results, it implies that in order to save fuel cost especially when operating smaller trucks, rolling resistance needs to be controlled to minimum values.

NOx, HC, CO and PM emission estimations

Diesel emissions per ton show some improvement with increasing truck size due increased capacity and engines fuel efficiency. Relationships between diesel emissions and total resistance (Grade + Rolling) verify this.

NOx and HC emissions

Figure 5-16 show the relationship between NOx and HC emissions by truck size and with increasing total resistance. The dotted lines indicate the operating conditions where normal field conditions are enveloped from 12% to 18%.

Considering the grade resistance of 8%, the operating rolling resistance vary from 4% to 10%. Above this range the rate of increase in emissions is much higher. Comparing the percentage increase in NOx and HC emissions; there is a mean decrease of 21% jumping from CAT785C to CAT793 model units, 45% from CAT793F to CAT797F and 57% from CAT785C to CAT797F model units.

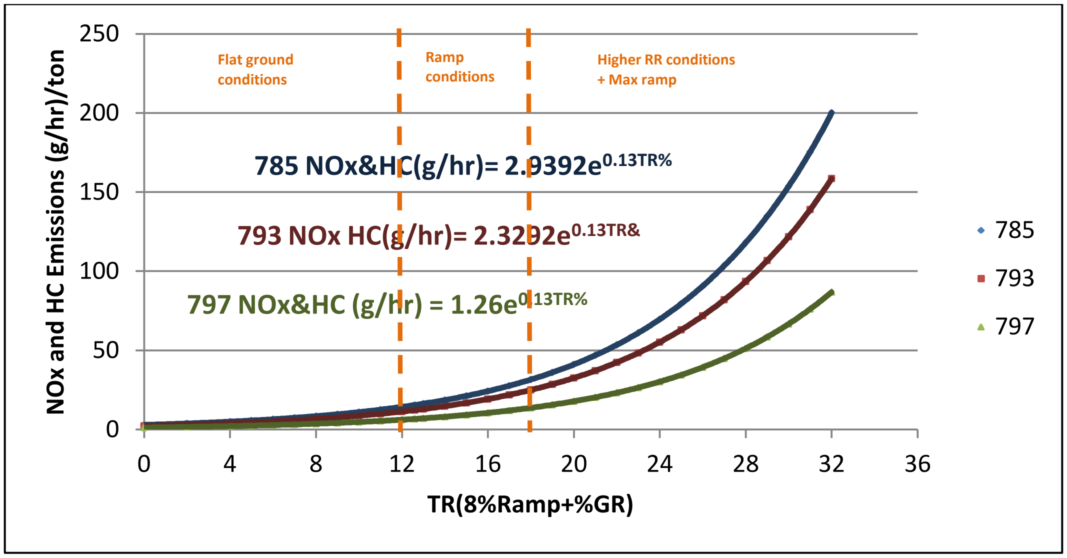


Figure 5-16: Relationship between TR with HC and NOx emissions for different truck sizes

CO emissions

CO emissions per ton are higher on smaller trucks than larger trucks. Emissions increase with increasing total resistance. Average improvement is 21% decrease in emissions jumping from CAT785C to CAT793F model units, 45% from CAT793F to CAT797F and 57% from CAT785C to CAT797F model units.

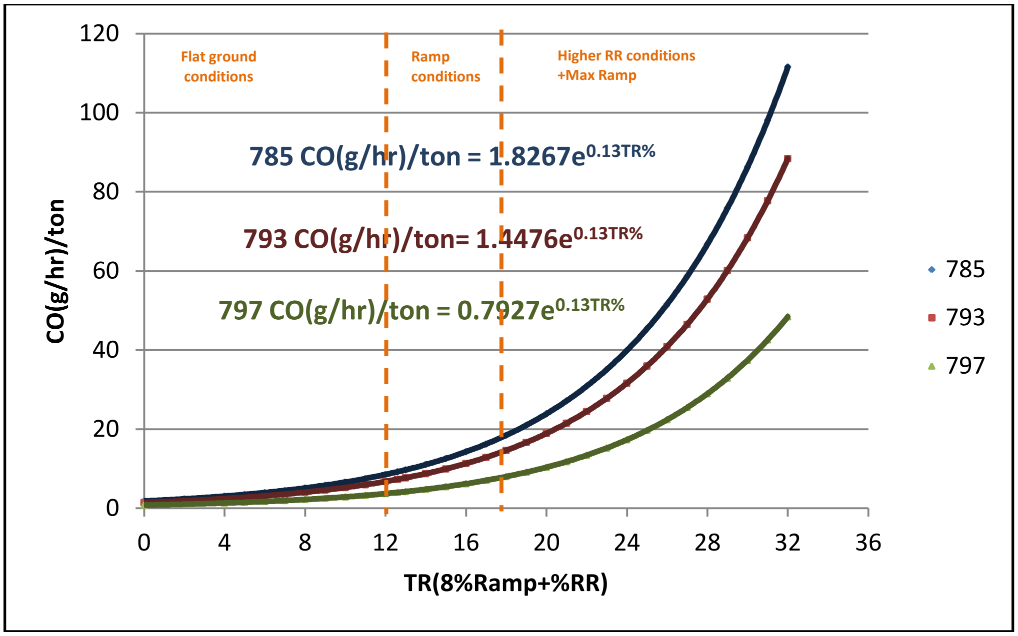


Figure 5-17: Relationship between TR and CO emissions

PM emissions

The PM emissions and total resistance relationship is similar to other emissions for the fact that; emissions per ton capacity decrease with increasing truck size and increase with increasing TR. The relationships are linear. Average percentage decrease in PM emissions with increasing truck size is 24% from CAT785C to CAT793F model units, 48% from CAT793F to CAT797F and 58% from CAT785C to CAT797F model units.

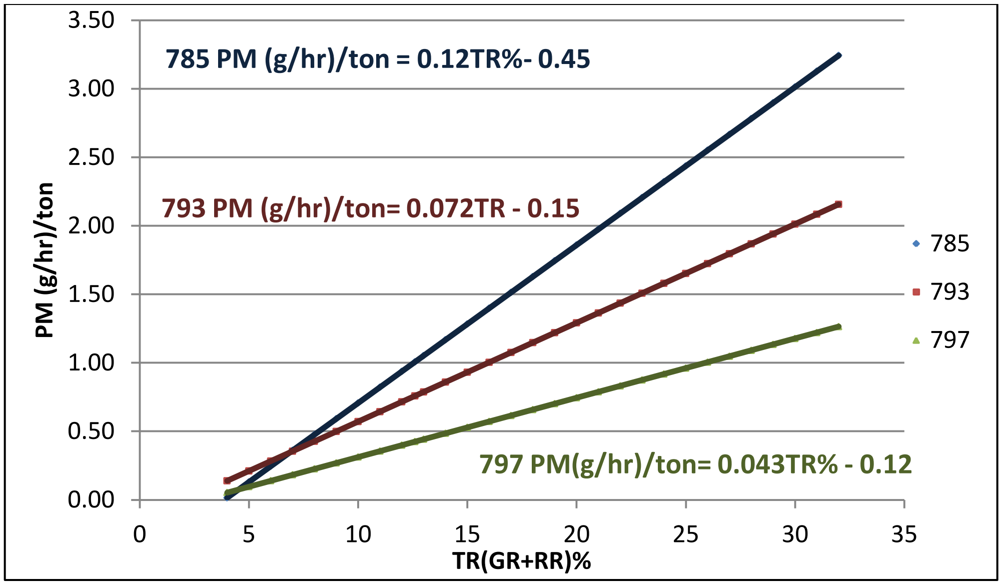


Figure 5-18: Relationship between TR and PM emissions

5.7 Section conclusion

Fuel consumption and diesel emissions are influenced by engine efficiency. Using data from OEMs; in this case DDC engines (used on Terex Unit Rig trucks) and MTU and Cummins engines (used on Liebherr trucks); it was observed that with increasing truck size fuel consumption per ton decreases. This is believed to be due to increased truck capacity and engine efficiency. Total fuel consumption per hour increased with truck size on MTU and Cummins engines while with DDC engines fuel consumption increased with size from 100 ton to 300 ton trucks and decreased on higher tonnage trucks (ranges from 320 to 400 ton).

Comparing different truck sizes on diesel emissions using DDC engines data, data collected by Joseph (2000 - 2003) on mine sites and report generated by Rawling and Unrau, (2008), emission factors were observed to decrease with truck size. This is due to engine modifications to increase efficiency in fuel consumption and emissions control. With incresing total resistance fuel consumption and emissions increased; whose impact was observed to be higher on smaller trucks.

6 DISCUSSION

Summary

From the above analysis it was apparent that with increasing hauler size,

- Width of haul roads and size of pit increases which necessitates more waste stripping.
- Haul road layer thickness increase with truck size where with wider roads required for larger trucks, the amount of construction material, time and construction resources increase.
- The rate of increase of rolling resistance is the same regardless the size of the hauler when crushed rock is used as wearing course material.
- On fuel consumption and emission, great savings are evident when using larger haulers.

Giving the dollar value to each of the component in additional to capital cost for each truck, the general idea of hauler size cost is presented insisting on its impact in mine planning.

Hauler costs estimations

The costs are estimates from field experience Joseph (2000-2012) has on different mine sites. Constant values were used not taking into considerations interest rates and costs variations with time.

Trucks cost

Truck cost is an estimate of purchasing cost per unit. It is assumed that the tires are changed once a year and the estimation is done for 10 years which is the life of trucks.

Truck	785	793	797
Capital cost	$2.25M	$3.8M	6M
Tire cost	$50K/tire	$80K/tire	$130K/tire

Construction material cost

Material	Cost $/t
Crushed rock	9
Gravel/Pit-run	3
Till mine spoil	3

Road maintenance cost

The rate of increase of rolling resistance is almost the same regardless size of trucks. Difference is on size of grader for road maintenance. For each road size the appropriate grader size for maintenance is selected.

Grader	Capital cost
14M- 4.3m	$300K
16M – 4.9m	$400K
24M- 7.3m	$480K

Fuel cost

Fuel cost is 0.8$/l; Note: Fuel is estimated in litres per ton for 10 years of truck operation.

Stripping cost

Stripping cost is estimated to be 3-5$/t. In this case an average of 4$/t is used.

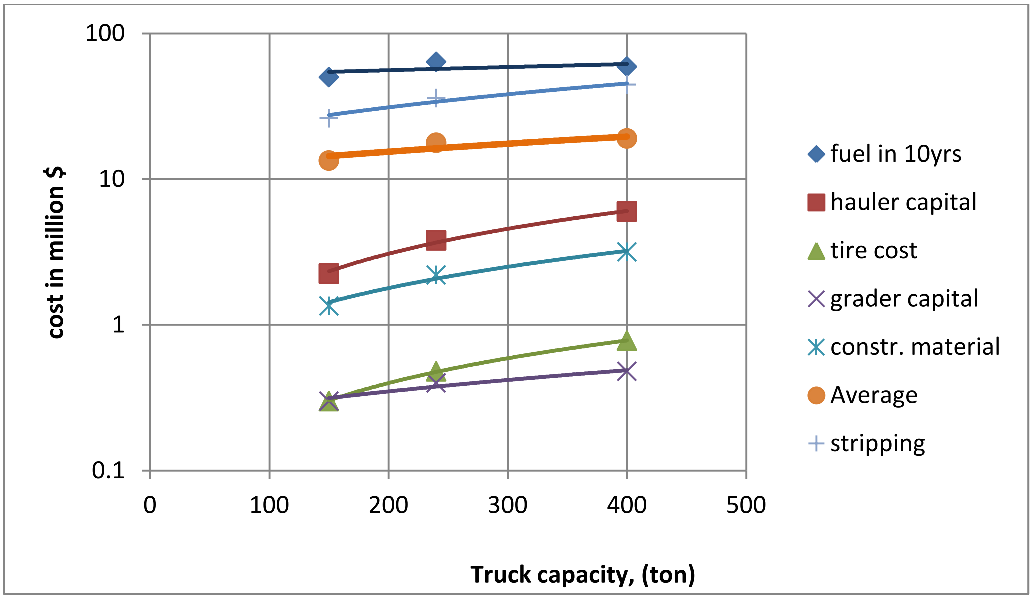


Figure 6-1: Cost comparison for Haulers

As illustrated in figure 6-1 the highest cost for truck operation was seen to be fuel closely followed by waste stripping costs to accommodate an incremental increase in truck and road size. Both were in order of magnitude higher than any capital or construction material cost. It was also observed that, the total average cost increases with increasing truck size. The benefits of using larger trucks need to be balanced against the capital and operating costs in size selection. The cost of emissions is hard to attribute a dollar value to, although it has severe impacts on human health and environment; that also need to be noted in making decisions.

Mine planning input

In additional to conventional mine planning considerations, the aspects of haul road size, haul road construction and maintenance and fuel consumption and emissions should be thought beforehand due to their huge cost impacts. From figure 2-1 description of the mine planning process, equipment size should be decided early on ore block modelling and when determining economic block value (EBV) as it affects cost at this stage and all other decisions on following stages. The effect of size need to be determined addressing all aspects and evaluate value for their applications against the costs.

7 CONCLUSION AND RECOMMENDATIONS

7.1 Summary of findings

The notion 'bigger is better' has been a focus for over a decade since 2000, and mine operators are cognisant of opportunities to phase out smaller trucks and employ bigger units with new and expanded projects. There are advantages noticed with higher capacity equipment but there are challenges as well.

When making decision on equipment size there are many factors to consider. This research was focused on road size, road construction requirements, rolling resistance, fuel consumption and emissions. Overall results show an increase in costs with increasing equipment size which should not be surprising. The increase in cost was 33% from CAT 785 to CAT 793, 9% from CAT 793 to CAT 797 and 46% from CAT 785 to CAT 797.

Larger trucks require wider roads and therefore more stripping is required thus impacting mining cost. Pit slopes are affected by the size of road; having wider roads, pit slopes decrease which increase pit size.

Haul road construction is dependent on size and weight of trucks among other factors. With larger trucks, thicker pavements and wider roads are required and therefore more construction material, time and construction resources. Using crushed rock as wearing course material, rolling resistance increase rates are the same regardless of truck size. The difference in maintenance cost is therefore dependent on grader size as a function of road size.

Regarding fuel consumption and diesel emissions per ton, there are huge improvements observed in larger trucks. This is due to increased capacity, reduced fuel consumption and improved engine efficiency as claimed by OEMs, endorsing the notion “bigger is better”. Huge savings are evident on fuel consumption when using larger trucks. On diesel emissions, the costs associated with human health and environmental effects, although they cannot be given a specific dollar value, have huge detrimental effects which are hard to undo and therefore should be given enough weight in decision making.

7.2 Contribution to engineering research and mining industry

This study opens new thinking on equipment size implications on mine planning by incorporating some aspects which are left out of the mine planning process and have high cost impacts. The notion 'bigger is better' which is the current focus in the industry is challenged with the results obtained which suggest that bigger is not necessarily better as observed with respect to road size and road pavement construction requirements. These and other challenges discussed in section 2.5.2 bring new opinion to equipment size. On the other side, this does not favour smaller over bigger trucks due to higher operating costs witnessed in fuel consumption and emissions. Balancing equipment size selection and qualitative aspects with size of operation need to be considered in making a decision.

The results obtained can be used in a customized fashion depending on location and stage of operation, whether it is the initial stages of mine planning or when making the decision to employ a different equipment size. When this information is improved to include different stages of mine planning and various operating conditions can provide useful data for future modelling using software such as 'Symphony'.

7.3 Recommended future work

The results obtained in this study give a general picture on the costs associated with hauler scale. The information used in this study is mainly from OEM and pre-collected data sources. For this information to be useful the following is recommended.

1. Applied loads used on road layer thickness calculations are estimated from static loads. Load variations due to dynamic conditions which are caused

by truck motion are not accounted. Field data collection can help determine the variations for different truck sizes to be used in layer thickness calculations for more realistic results employing dynamic truck data. These variations might increase loading up to an additional 50% which is high to be neglected.

An interesting subject in road construction can also be balancing increase in haul road grade, which means less stripping ratio and less haul road construction material against operating costs and safety.

2. Rolling resistance estimation done in this study provides cumulative efforts of load application for the surface course material used (crushed stone). This might not be the case for shorter time periods and different materials with the same loads applied. More tests are suggested on rolling resistance estimation to determine the effects of individual loads and different wearing course material types on haul road construction.

3. The data used for fuel consumption are fewer and mainly from equipment manufacturers. However for the same truck capacity fuel consumption might differ from one engine manufacturer to another. It is also believed from a field experience that bigger trucks consume more fuel than stated by OEMs. I would suggest as an extension of this study to determine the actual values in field operations for different truck sizes and models.

4. Emissions can be more reflective of actual practice if measured from the actual operation than estimated. There are more factors influencing emissions which are not covered in this study such as age of the equipment and others. More study on other factors affecting emissions need to be done.

8 REFERENCES

1) Baumann, S. (1999). Review your assets to determine maximum fleet size. A case study history of Glamis Gold's Operation, www.glamis.com.

2) Berkhimer, E. (2011). Selection and sizing of excavating, loading and hauling equipment. In P. Darling, *SME Mining engineering Handbook, 3rd Ed* (p. Chapter 10.4).

3) Boucom, J. (2011). The evolution pf Trucks is changing interactions and pruductivity at minesites. *Allen & Holt consulting company monthly articles, 110*.

4) Boucom, J. W. (2008). Optimizing powered investment in sufrace coal application. *available at www.minexpo.com/Presenations/boucom.pdf*.

5) Bozorgebrahimi, E. (2004). *Evaluation of the haulage truck size effects on open pit mining. PhD Thesis.* University of British Columbia.

6) Caterpillar. (1998). *Caterpillar Performance handbook. Edition 29.* Peoria IL, USA: Caterpillar Inc.

7) Caterpillar. (2008). *Ultra class trucks, presentation to Univeristy of Alberta MINe 420/620 class by Faher, D. and O'Neill, B.* Edmonton, Albrta.

8) Caterpillar. (2012). *Caterpillar performance handbook Ed 49.* Peoria, Illinois USA: Caterpillar Inc.

9) Dietz, M. (2000). Introduction. In W. A. Hustrulid, *Slope stability for surface mine* (p. xv).

10) EPA. (2005). *Emission reduction incentives for off-road diesel equipment used in th port and construction sectors.*

11) Filas, F. J. (2002). Excavation, loading and material transport. In R. L. Lowrie, *SME Mining Reference Handbook* (pp. 215-241). Littleton, CO, USA: Society of Mining, Metallurgy and Exploration Engineering.

12) Hays, M. R. (1990). Trucks. In B. A. Kennedy, *Surface Mining Handbook* (pp. 672-691). Littleton, CO, USA: Society of Mining, Metallurgy and Exploration Engineering.

13) Jaques, A. (1992). *Canada's greenhouse gas emissions; Estimates for 1990.* Environmental Canada report EPS 5/AP/4.

14) Joseph, T. G. (2002). OsEIP: The oil sand - equipment interaction program. *CIM Bulletin, 95 (1064)*, (pp. 58-61).

15) Joseph, T. G. (2003). Large mobile mining equipment operating in soft groud. *Proceedings of International Mining Congress and Exhibition of Turkey (IMCET)*, (pp. 143-147,588). Antalya, Turkey.

16) Kaufman , W. W., & Ault, J. C. (1977). The design of surface mine haul roads. In *A manual information circular 8758.* Washington DC : US Bureau of mines.

17) Kecojevic, V., & Komljenovic, D. (2010). Haul truck fuel consumption and CO_2 Emission under various engine loads conditions. In *SME Mining Engineering Journal, Vol 62 No 12* (pp. 47-52). Society of Mining, Metallurgy and and Exploration.

18) Knapton, J. (1988). *The structural design of heavy duty pavement for ports and other industries.* London, England: British Port Federation.

19) Krause, G. (2001). Large Heavy Hauler. *Is bigger better? SMART Seminar 6.* Edmonton, Alberta

20) Lashgari, A., Johnson, C., Kecojevic, V., Lusk , B., & Hoffman, J. M. (2013). NOx emissions of equipment and blasting agents in surface mining. In *SME Mining Engineering Journal. Vol 65* (pp. 34-41). Society of Mining, Metallurgy and Exlporation Engineering.

21) Leslie, D. R. (2000). *Diesel emissions evaluation for the surface mining industry*. SMART conference.

22) Lizzote, Y. (1988). Economical and technical relations between open pit design and equipment selection. In J. Singhal, *Mine Planning and Equipment Selection.*

23) Morgan, J. R., Tucker, J. S., and McInnes, D. B. (1994). A mechanistic design approach for unsealed mine haul roads. In *Pavement design and perfomance in road construction 1412* (pp. 68-81).

24) Nasab, H. A. (2011). *Open pit long term planning stages. MinE 631 notes.*

25) Noble, A. C. (1992). Ore reserve/resource estimation. In H. L. Hartman, *SME Mining Engineering Handbook 2nd Ed* (pp. 334-359). Littleton, Colorado.

26) P. Gilewicz: ‘Large truck report’, *World Mining EquipmentMagazine*, July/Aug, 2001, <www.parkerbaymining.com>.

27) Perloff, W. H. (1975). Pressure distribution and settlement. In *Foundation Engineering Handbook* (pp. 14-19).

28) Roman, P. A., and Daneshmand , L. (2000). Economics of scale in mining - assesing upper bounds with simulation. *The Engineering Economist, 45:4*, 326-338.

29) Runge, I. (1998). *Mining economics and strategy.* Littleton, CO, USA: Society of Mining, Metallurgy and Exploration Engineering.

30) Sharma, A. (2009). *Scale tire - oil sand interaction, Master Thesis.* University of Alberta.

31) Singh, R. B., Rawling, M., and Unrau, G. (2008). Assesment of mobile emissions in the Athabasca oil sand region - high resolution non-road emission factor model. *ACE conference paper 461.*

32) Singhal , R. K., Fytas, K., and Collins, J. L. (1986). *Optimization of loading and hauling equipment productivity in surface mining.* St. Louis: Society of Mining, Metallurgy and Exploration Engineering.

33) Tannant , D., & Regensburg, B. (2001). *Guidelines for mine haul road design.* Edmonton, Alberta: School of Mining and Petroleum Engineering, University of Alberta.

34) Thompson , R. J., & Visser, A. T. (1997a). A mechanistic design procedure for surface mine haul roads. In *Int. Journal of Surface, Reclamation and Environment, 11* (pp. 121-128).

35) Thompson, R. J. (2010). Mine haul road design and management best practice for safe and cost effective effecient truck haulage. *Society of Mining, Metallurgy and Exploration Annual Meeting*, (pp. 1-10). Phoenix, Arizona.

36) Thompson, R. J. (2011a). *Mine haul road design, constructionand maintenance management.*

37) Thompson, R. J. (2011b). Building better haul roads. *Engineering and Mining Journal*, 49-53.

38) Thompson, R. J. (2011c). Design, construction and maintenance of haul roads. In D. P, *SME Mining Engineering Handbook, 3rd Ed* (Chapter 10.4).

39) Thompson, R. J., & Visser , A. T. (2000). Selection parameters for mine haul road wearing cousre material. *International Journal of Surface Mining, Reclamation and Environment*, 1-17.

40) Thompson, R. J., & Visser, A. T. (1997b). An introduction to the integrated design of surface mine haul roads. *International Journal of Surface mining, Reclamation and Environment*. 11:3.

41) Thompson, R. J., & Visser, A. T. (2006). The impact of rolling resistance on fuel, speed and costs. *Continuous improvement case study*.

42) Whittle, D. (2011). Open pit mine planning and design. In P. Darling, *SME Mining Engineeering Handbook, 3rd Ed* (Chapter 10.2).

APPENDIX

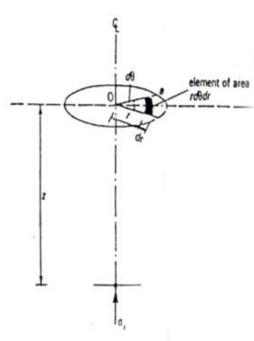
8.1 Appendix A

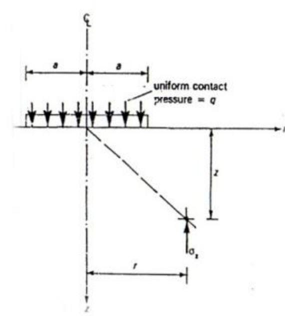
Haul road layers thickness estimations.

A 1: Influence factors for vertical stress due to a uniformly-loaded circular area

z/a	r/a 0	0.2	0.4	0.6	0.8	1.0	1.2	1.5	2.0	3.0
0	1.0	1.0	1.0	1.0	1.0	0.5	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.2	0.804	0.798	0.779	0.735	0.630	0.383	0.154	0.053	0.017	0.004
	0.188	0.193	0.208	0.235	0.260	0.085	-0.078	-0.044	-0.016	-0.004
0.4	0.629	0.620	0.592	0.538	0.443	0.310	0.187	0.086	0.031	0.008
	0.320	0.323	0.327	0.323	0.269	0.124	-0.008	-0.045	-0.025	-0.008
0.6	0.486	0.477	0.451	0.404	0.337	0.256	0.180	0.100	0.041	0.011
	0.378	0.375	0.363	0.382	0.254	0.144	0.045	-0.021	-0.025	-0.010
0.8	0.375	0.368	0.347	0.312	0.266	0.213	0.162	0.102	0.048	0.014
	0.381	0.374	0.351	0.307	0.238	0.153	0.075	0.006	-0.018	-0.010
1.0	0.293	0.288	0.270	0.247	0.215	0.179	0.143	0.098	0.052	0.017
	0.353	0.346	0.321	0.278	0.220	0.154	0.092	0.028	-0.010	-0.011
1.2	0.232	0.228	0.217	0.199	0.176	0.151	0.126	0.092	0.053	0.0.19
	0.315	0.307	0.285	0.248	0.201	0.149	0.100	0.044	0.000	-0.010
1.5	0.168	0.166	0.159	0.148	0.134	0.119	0.103	0.080	0.051	0.021
	0.256	0.250	0.233	0.207	0.174	0.137	0.102	0.057	0.014	-0.007
2.0	0.106	0.104	0.101	0.096	0.090	0.083	0.075	0.063	0.045	0.022
	0.179	0.181	0.166	0.152	0.134	0.113	0.093	0.064	0.028	0.000
3.0	0.051	0.051	0.050	0.049	0.047	0.045	0.042	0.038	0.032	0.020
	0.095	0.094	0.091	0.086	0.080	0.073	0.066	0.054	0.035	0.011
4.0	0.030	0.030	0.029	0.028	0.028	0.027	0.026	0.025	0.022	0.016
	0.057	0.057	0.056	0.054	0.051	0.048	0.045	0.040	0.031	0.015
5.0	0.019	0.019	0.019	0.019	0.019	0.018	0.018	0.018	0.016	0.012
	0.038	0.038	0.037	0.036	0.035	0.034	0.031	0.028	0.025	0.015
10.0	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.004	0.004
	0.010	0.009	0.009	0.009	0.009	0.009	0.009	0.009	0.008	0.008

Top line = A : bottom line = B $\sigma_z = q(A + B)$ *(see fig. 2)* $\varepsilon_z = q(1 + \nu)[(1 - 2\nu)A + B]/E$





A 1 was used along with Bousinnesq ground stress bulb to estimate stress variations with depth under the tire.

Sample calculations

Sub-grade depth from surface for CAT 797F

σ = 753.93KPa

Limiting strain Ɛ= 1964 micro-strain

b=1.23m

<u>Sub-grade depth computation;</u>

Resilient modulus, E_r =40MPa

Exerted stress at depth z, σ_z /P = σ*(A+B)

Where A&B are influence factors for uniformly-loaded circular area in table A1

a) At Z/b= 3, Z= 3*1.23 =3.69m,

σ_z = 754*0.146

= 110.084KPa

$\varepsilon_z = \sigma_z / E_r$

= 110.084 KPa/40MPa= 2752 micro-strain (which is upper closer to 1964 micro-strain)

b) At Z/b =4, Z=4* 1.23 = 4.92m

σ_z = 754*0.087

=65.598KPa

ε_z = 65.598KPa/40MPa= 1640 micro-strain (which is lower closer to 1964 micro-strain)

Interpolating between the values, 1348 micro-strain will be at depth Z=**4.56m**

The description of this process is presented on table A 2.

A 2: Process description for road layers thicknesses estimation for CAT797F

Z	A+B	stress at depth z	**Surface, ε**	**Base, ε**	**sub-base, ε**	**sub-grade, ε**	**req depth, m**
			E_r=330	**E_r=245**	**E_r=130**	**E_r=40**	
0.00	1.00	754.00	2285	3078	5800	18850	
0.25	0.99	747.97	2267	3053	5754	18699	
0.49	0.95	715.55	2168	2921	5504	17889	
0.74	0.86	651.46	1974	2659	5011	16286	
0.98	0.76	570.02	1727	2327	4385	14251	
1.23	0.65	487.08	1476	1988	3747	12177	1.25
1.48	0.55	412.44	1250	1683	3173	10311	
1.85	0.42	319.70	969	1305	2459	7992	2.22
2.46	0.29	214.89	651	877	1653	5372	
3.69	0.15	110.08	334	449	847	2752	4.56
4.92	0.09	65.60	199	268	505	1640	
6.15	0.06	42.98	130	175	331	1074	
12.30	0.02	11.31	34	46	87	283	

8.2 Appendix B

Rolling resistance estimation

Using equation 3-12 rate of increase in rolling resistance for 3 truck sizes were estimated as shown in B 1. The average difference in rolling resistance increase between trucks was obtained to be 0.004% which is negligible variation.

B 1: Estimates of rolling resistance increase rate

	Rate of RR increase			
days	CAT 797F	CAT 793F	CAT 785C	%RR difference
0	2.33	2.33	2.33	0.001
1	2.38	2.38	2.38	0.002
2	2.43	2.43	2.44	0.002
3	2.50	2.50	2.50	0.002
4	2.57	2.57	2.57	0.003
5	2.63	2.63	2.64	0.003
6	2.68	2.68	2.69	0.004
7	2.72	2.72	2.73	0.005
8	2.75	2.75	2.75	0.005
9	2.77	2.77	2.77	0.006
10	2.78	2.78	2.78	0.006
11	2.78	2.78	2.79	0.006
12	2.79	2.79	2.79	0.006
Average				0.004