# GUIDELINES FOR MINE HAUL ROAD DESIGN

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# Preface

The idea of developing a haul road manual or collection of guidelines was initiated by the late Professor Muirhead at the University of Alberta in 1999. Support and financial contributions for this work were obtained from NSERC, SMART (Surface Mining Association for Research and Technology) ATCO Power, and Finning. Both Syncrude Canada Ltd. and Suncor Ltd. provided access to road design data and methodologies. Syncrude Canada Ltd.'s internal reports were instrumental in verifying the strain-based design approach for haul roads advocated in this manual.

Two closely related documents form a basis for this manual. The oldest is the report by Kaufman and Ault (1977) entitled *Design of Surface Mining Haulage*. Monenco (1989) took the Kaufman and Ault report and updated it to reflect conditions relevant to Canadian mines. The Monenco report is unpublished and difficult to obtain. The questionnaire survey found in the Monenco report was modified and repeated in 1999 for this document.

Content from the M.Sc. thesis by Kumar (2000) is also used in this document, especially in sections dealing with design of a haul road cross-section. Bruce Regensburg compiled the section on haul road economics. In addition, haul road design issues were also gathered from various published sources that are referenced in the *Guidelines for Mine Haul Road Design*.

This manual is not meant to be comprehensive, rather it is intended to cover most of the issues important to haul road design for rear-dump trucks that have payloads greater than about 200 tonnes. This document is meant as an aid to Mining Engineers, Geotechnical Engineers and Management in constructing quality haul roads. Haul road design is usually the product of a plan from the Mining or Civil Engineer with construction specifications from the Geotechnical Engineer. The Mining Engineer will work on the geometric parts of the haul road including vertical and horizontal curves, widths, super-elevation and location of the road while the Geotechnical Engineer will provide the material specifications and placement criteria.

Good haul road construction and maintenance practices are a key part of operating a cost-efficient fleet of trucks. Haul roads should be considered an important asset to a mining operation, in the same manner as trucks and shovels.

While much effort was expended to verify equations, graphs, and tabular data adopted from other sources, errors may have been missed. Therefore, users of this document are encouraged to contact the authors if errors are discovered. This will enable the first version of this manual to be improved and will allow it to evolve to better meet the needs of the mining industry.

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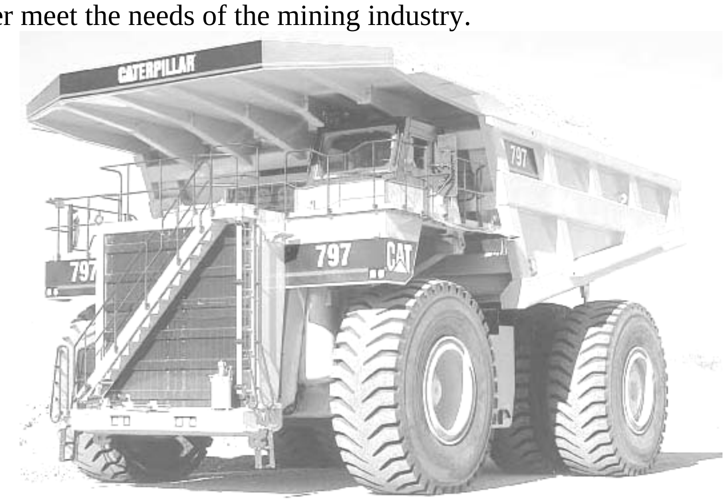

# 1 SURVEY OF HAUL TRUCKS & ROADS FOR SURFACE MINES

## 1.1 Introduction

To assess current haul road design and construction procedures used in Canada, a questionnaire was sent to 37 surface mines in western Canada, of which 13 replied. The questionnaire asked for information about:

- Equipment used – haul trucks, haul road construction and maintenance equipment.
- Method of haul road construction and maintenance – haul road geometry, construction materials, and symptoms of haul road deterioration and maintenance procedures.
- Procedure(s) for haul road design.

The questionnaire was sent out in December 1998 and responses were received as late as July 1999. Of the 13 responding mines, eight were coal mines, three were metal mines, one was an oil sand operation and one was a graphite mine. Some mines had very large yearly production (e.g., Syncrude Canada Ltd. mines 260 million metric tonnes (mt) of oil sands and waste per year) whereas others were relatively small operations (e.g., Mount Polley handles 14 million mt (ore and waste) per year). Most of the coal mines handled roughly 25 million tonnes per year. The average stripping ratio varied from 0.8:1 (Syncrude Canada Ltd.) to 18.9:1 (Bullmoose mine) but most of the coal mines had a stripping ratio of less than 10:1.

A similar survey was done by Monenco (1989), in which 13 mines participated. In fact, six operations are common between these two surveys, but they have grown significantly in size over the past decade. In this section, questionnaire responses are summarized and compared to those gathered by Monenco (1989).

Information was also gathered from haul truck manufacturers and suppliers about the specifications of present and future large haul trucks. This information included gross vehicle weight (GVW), turning radius, truck dimensions, etc. that were deemed to affect the haul road design and construction procedures.

Another factor affecting the design of haul roads is the type of tire used on haul trucks. Inflation pressure and size of the tire determines the size, shape and magnitude of the stress bulb in the layers of a haul road (especially in the upper layers). Tire specifications such as size, footprint area, shape of footprint and designed inflation pressure, were gathered from Michelin and other tire manufacturers.

Design and construction of haul roads is influenced, largely, by the climatic conditions at the mine site. Most Canadian mines experience freezing and thawing of roadbed for a major portion of the year. Thus, the use of materials that can bear freezing and thawing becomes essential.

## 1.2 Haul Trucks and Construction/Maintenance Equipment

Different mines use a variety of haul trucks for ore and waste transportation. As expected, the oil sand operation, which is the largest handler of materials, used the largest trucks. Their fleet included CAT 797 and Haulpak (Komatsu) 930E (September 1999), the two largest haul trucks available as of 1999 (payload capacity – 300mt). Most of the coal mines used trucks with payload capacities around 200mt, while some of the smaller operations used trucks with payload capacities less than 100mt. Table 1-1 shows the truck models operating in these mines as of 1999.

Table 1-1 Haul trucks in use as of 1999.

| Make | Model No. | No. of trucks | GVW (mt) | Payload (mt) |
|---|---|---|---|---|
| Caterpillar | CAT 769 C | 4 | 68 | 32 |
| Caterpillar | DJB 25 C | 1 | 42 | 23 |
| Caterpillar | CAT 777 B | 6 | 161 | 80 |
| Caterpillar | CAT 776 A | 1 | 250 | 120 |
| Caterpillar | CAT 776 D | 4 | 250 | 150 |
| Caterpillar | CAT 785 | 8 | 250 | 136 |
| Caterpillar | CAT 789 | 11, 43* | 317.5 | 180, 172* |
| Caterpillar | CAT 793 | 34 | 415 | 218 |
| Dresser Haulpak | 630 E | 11 | 286 | 170 |
| Dresser Haulpak | 830 E | 53 | 399 | 231 |
| Haulpak | 930 E | 8 | 480 | 290 |
| Euclid | R 170 | 12 | - | - |
| Titan | 3315(B/C) | 33 | 285 | 170 |
| Unit Rig | MT 4400 | 5 | 392.3 | 236 |
| Unit Rig | M 36 | 7 | - | - |
| Wabco | 120 | 8 | 204 | 109 |
| Wabco | 170 | 27 | 268 | 154 |
| Wabco | 630 E | 3 | - | - |

* Different mines used the same model with different pay loads; the number used and payloads are given in order.

Nearly all mines used graders, dozers, and dump trucks for haul road construction. Graders, dozers and water trucks were used for haul road repair and maintenance work. A summary of equipment used for haul road maintenance and material loading is given in Table 1-2. Dump trucks play a dual role in road construction. Besides transporting construction materials, they are used for compacting various layers during haul road construction. One mine used a sheep-foot compactor for clayey materials and a smooth vibratory drum roller for granular material. Water sprinkling trucks are used at all mines for dust suppression. Except for the compactors, Monenco (1989) reported use of similar haul road construction and maintenance equipment.

Table 1-2 Type of loading and haul road maintenance equipment.

| Equipment | Mines using |
|---|---|
| Haul road maintenance equipment | |
| Scraper | 7 |
| Dozer | 11 |
| Grader | 13 |
| Water Truck | 13 |
| Wheel Tractor | 7 |
| Sand Truck | 1 |
| Loading equipment | |
| Cable Shovel | 11 |
| Hydraulic Shovel | 4 |
| Backhoe | 6 |
| Dragline | 2 |
| Front End Loader | 12 |

Haul trucks used in surface mines have grown significantly in terms of size and capacity (Table 8-3). In 1989, the largest trucks available were of less than 200mt-payload capacity, but by 1999, the payload capacity rose to more than 300mt. Considering the fact that increases in the size of haul trucks were virtually at a stand still during the early half of this decade, (due to limitations of tire technology for larger trucks), this recent increase in haul truck size is significant. Larger haul trucks are being designed, produced, and accepted by the industry for one important reason: economy of scale. Almost all of the large haul trucks in current use have two axles (with four tires on the rear axle). The use of two axles provides better manoeuvrability and smaller steering radius. The limiting factor in the design of larger haul trucks is the design of tires to match the trucks.

Haul trucks with gross weights of more than 500mt (payload > 300mt) have been recently introduced at some mines. Correspondingly, the load per tire has increased to more than 85mt.

Apart from haul road construction materials, the geometry of haul roads also requires modifications to accommodate the new larger trucks. The haul road width depends upon the width of the largest truck in use. The maximum truck width has gone up from 7m in 1989 to 9m in 1999. Moreover, the turning radius of the trucks, on average, has increased by 10% over that of a generation earlier. For example, a CAT 793C has a turning radius of 15m but a CAT 797 has a turning radius of 16m. The increase in turning radius became significant as the length of the truck increased from 12m for CAT 793C to 14.5m for CAT 797. Larger turning radius and width of road is required to accommodate these trucks. More importantly, the maximum speed of these trucks has increased in most cases by 8 to 10km/hr. For example, TI 252 and T 262 trucks by Liebherr have a maximum speed of 51km/hr whereas next generation trucks from same company, namely the TI 272 and T 282 have a maximum speed of 68 and 64km/hr respectively. This also impacts the haul road geometry in terms of stopping distance. Other haul road dimensions would also have to increase to fit these larger, faster trucks.

## 1.3 Haul Road Length

The 13 mines surveyed had a total of 50km of in-pit road with an average life expectancy of 1.4 years and a total of 100km of ex-pit roads with an average life expectancy of 8 years (Table 1-3). The haul road length varies widely from mine to mine. Temporary haul road lengths ranged from 0.5km to 10km whereas the length of permanent haul roads varied from 1.3km to 14km. Monenco (1989) reports a total of 50km in-pit and 180km of ex-pit roads for the 13 mines surveyed. But it cannot be said that ex-pit haul road lengths in surface mines have decreased in the past ten years because different mines were involved in the two surveys.

Table 1-3 Haul road length and life span.

| Material | Cumulative length (km) | Average* expected road life (years) |
|---|---|---|
| In-Pit | | |
| Product haul | 17.3 | 1.6 |
| Waste haul | 12.8 | 1.1 |
| Common haul | 20.6 | 1.7 |
| Total In-Pit = | 50.7 | 1.4 |
| Ex-Pit | | |
| Product haul | 74.8 | 10 |
| Waste haul | 13.2 | 7 |
| Common haul | 11.7 | 5 |
| Total Ex-Pit = | 99.7 | 8 |

* Average weighted for number of mines reporting

## 1.4 Haul Road Geometry

Haul road geometry is comprised of many factors including maximum grade, cross slopes of road, running width, etc. The maximum haul road gradient was limited to 10% but generally, gradients more than 8% were avoided. Maximum curve super-elevation was generally limited to 4% and speed limits were imposed at tighter curves to reduce the required super-elevation. Maximum road cross slope varied widely from mine to mine (1.5% to 4%) depending upon the precipitation and nature of soil but a 2% cross slope was considered optimum for most mines. Table 1-4 summarizes the data collected from the mines.

Ditch sizes varied widely depending on precipitation. Average ditch widths and depths were 3m and 1m respectively. The height of safety berms was generally calculated as 1/2 to 3/4 of the largest tire diameter in use and thus varied from 1.2m to 3.5m.

The breaking distance limitation was not considered at some mines, but in others, it was limited by law (e.g., Section 4.36 Art. 4921 H, S, R code for mines in British Columbia). The geometry of run-away lanes is a function of final velocity, road grade, acceleration due to gravity, and rolling resistance, and thus varied from mine to mine. On average, run-away lanes had a length of 100m with a gradient of 25%.

Monenco (1989) reported similar slopes or gradients for the running surface. One notable change over the past ten years is that running width has increased from an average of 25m in 1989 to 30m in 1999 and height of safety berms has grown from an average of 1.5m in 1989 to 2.5m in 1999. The increased dimensions can be attributed to increases in average size of haul trucks used.

Table 1-4 Haul road geometry.

| Item | Mine number | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| Max. Grade (%) | 10 | 10 | 10 | 10 | 8 - 12 | 10 | 10 | 5[j] | 7.5 | 8 | 10 | 8-10 | 6-8 |
| Max. Curve super-elevation (%) | 3 - 4 | 3 | - | 4 | 3[f] | - | g | k | 4 | 5 | - | 2-3 | 5 |
| Maximum road cross-slopes (%) | 3.25 | 1.5 | - | 2 | 3 | - | h | - | 4 | 0 | 3 | 2 | 5 |
| Min. running width (m) | 31 | 30 | 24 | 25 | 30 | 30 | 30 | 20 | 28 | 25 | 15 | 25 | 28[m] |
| Ditch sizing (total width x depth) (m) | 3.5x0.9 | 3x1 | e | 3x1.5 | - | 3x1 | i | 4x1 | 3.5x0.9 | 2x2 | - | 1x1 | - |
| Avg. height of safety berms (m) | 2.55[a] | 2.7 | 3 | 3.5 | 1.5 | 2 | 2 | 1.6 | 2.6 | 3 | 1.2 | 2.0 | 2[a] |
| Maximum breaking distance limitation (m) | - | - | - | - | | 33.55 | - | - | 84[l] | - | - | 50 | - |
| Number of lanes | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Runaway lanes: Max. Gradient (%) | 25 | 20 | 15 | 30 | - | - | - | - | 20 | 15 | - | - | 12-14 |
| Avg. Length (m) | B | 150 | 100 | 150 | - | - | - | - | 62 | - | - | - | 70-80 |
| Spacing (m) | C | 30[d] | 1000 | - | - | - | - | - | 240 | - | - | - | 30[d] |

a - 3/4 of largest tire diameter

b - function of entry velocity, acceleration due to gravity, road grade, and rolling resistance

c - function of final velocity, road grade, acceleration due to gravity, and rolling resistance

d - 30m vertical spacing on 8% ramp, shorter ramp with 7.5m vertical spacing also used

e - drainage ditch were of depth 0.5m - 1.5m

f - not generally used

g - not many curves, they are generally flat

h - very slight grade to facilitate runoff

i - 1m deep and 2m wide at base

j - 3% loaded, 5% empty

k - 200/radius of curvature (m)

l - @ 10% grade - 84m, section 4.36 Art. 4921 H, S, R code for mine in British Columbia

m - 3 times the width of largest haul truck

## 1.5 Haul Road Construction Materials

Most of the mines used no imported material for haul road construction, thus minimizing the haul road construction cost, however geotextiles were used by one of the mines while another mine constructed a test pad of sulphur, tailing sand and lean oil sand. Roller compacted concrete was tested for the surface layer of one haul road (Table 1-5 and Table 1-6).

Table 1-5 Materials used for road construction (except for road surface).

| Construction material | No. of mines using | Percentage |
|---|---|---|
| Run of mine (waste) | 8 | 73 |
| Sandstone | 3 | 27 |
| Glacial till | 1 | 9 |
| Sand | 1 | 9 |
| Pit run gravel | 1 | 9 |
| Shale | 2 | 18 |
| Siltstone | 1 | 9 |
| Crushed stone | 1 | 9 |
| Rut & roll fill | 1 | 9 |

Table 1-6 Materials used for road surface.

| Construction materials | No. of mines using | Percentage |
|---|---|---|
| Crushed run of mine (waste) | 9 | 82 |
| Crushed pit run gravel | 4 | 36 |
| Shale | 1 | 9 |
| Plant coarse reject | 1 | 9 |
| Crushed sandstone | 1 | 9 |

Comparison with the report by Monenco (1989) shows that haul road construction materials have not changed over the last decade although the thickness of different layers has increased marginally with use of larger haul trucks.

## 1.6 Symptoms and Causes of Haul Road Deterioration

Potholes, rutting, and settlement were major symptoms observed by almost all the mines (Table 1-7). Frost heave and wash boarding were also experienced. The running surface of the road suffered mostly due to precipitation/runoff, heavy traffic volume, spring breakup, and vehicle spillage. Main causes of deterioration to the base layer were spring breakup, precipitation/runoff, heavy traffic volume and poor compaction (Table 1-8). Poor compaction, high ground water level and precipitation were major causes of deterioration to other layers. Monenco (1989) reports similar symptoms and causes for haul road deterioration.

Table 1-7 Symptoms of haul road deterioration.

| Symptoms | No. of mines experiencing | Percentage |
|---|---|---|
| Potholes | 10 | 91 |
| Soft ground – rutting | 9 | 82 |
| Settlement | 8 | 73 |
| Slippery when wet | 7 | 64 |
| Washboarding | 6 | 54 |
| Frost heave | 4 | 36 |
| Loose surface materials | 3 | 27 |
| Water drainage problem | 1 | 9 |
| Coal seam crossing, back break | 1 | 9 |
| Rolling (large shear plane) | 1 | 9 |

Table 1-8 Causes of haul road deterioration, number of mines reporting (%).

| Causes | Sub grade | Sub base | Base | Surface |
|---|---|---|---|---|
| Dust / Binder deficiency | 0 (0) | 0 (0) | 1 (9) | 4 (36) |
| Gravel deficiency | 0 (0) | 0 (0) | 1 (9) | 7 (64) |
| Heavy traffic volume | 1 (9) | 1 (9) | 5 (45) | 6 (54) |
| High ground water level | 1 (9) | 1 (9) | 3 (27) | 4 (36) |
| Ice and snow | 0 (0) | 0 (0) | 1 (9) | 4 (36) |
| Operator's driving technique | 0 (0) | 0 (0) | 0 (0) | 0 (0) |
| Poor compaction | 3 (27) | 3 (27) | 3 (27) | 2 (18) |
| Precipitation / Runoff | 3 (27) | 3 (27) | 5 (45) | 10 (91) |
| Spring breakup | 2 (18) | 2 (18) | 6 (54) | 7 (64) |
| Vehicle spillage | 0 (0) | 0 (0) | 1 (9) | 6 (54) |
| Truck too heavy for road | 0 (0) | 0 (0) | 2 (18) | 3 (27) |
| Poor maintenance | 1 (9) | 1 (9) | 1 (9) | 1 (9) |
| Base settlement | 0 (0) | 0 (0) | 1 (9) | 0 (0) |

Rock drains and culverts were the most popular provisions for water crossing, while one of the mines used 0.61m diameter pipes for this purpose.

## 1.7 Haul Road Maintenance

Grading, resurfacing and plowing-scarifying-sanding were practiced at most mines to improve the haul road trafficability (Table 1-9). Some mines resorted to excavation and then backfilling up to sub-grade level for major haul road failures while others found raising the haul road grade a better solution. For dust suppression, most of the mines depended on water sprinkling while some mines sprayed calcium chloride or oil on the running surface (Table 1-10). Monenco (1989) confirms the use of similar haul road maintenance methods but for dust suppression also documents the use of saline ground water, potash and chemical additives such as calcium lignosulfate, Bio-Cat 300-1.

Table 1-9 Maintenance activities taken to improve trafficability.

| Maintenance activity | No. of mines | Percentage |
|---|---|---|
| Grading | 11 | 100 |
| Resurfacing | 10 | 91 |
| Road realignment | 7 | 64 |
| Plowing-scarifying-sanding | 10 | 91 |
| Excavate/Backfill soft spots up to: | | |
| Sub grade | 3 | 27 |
| Sub base | 4 | 36 |
| Base | 4 | 36 |
| Surface | 7 | 64 |
| Raising grade | 8 | 73 |
| Ditch / Culvert maintenance | 1 | 9 |

Table 1-10 Methods used for dust suppression.

| Methods | No. of using | Percentage |
|---|---|---|
| Water sprinkling | 11 | 100 |
| Oil sprinkling | 1 | 9 |
| Calcium chloride | 3 | 27 |

Different mines followed widely varying maintenance schedules depending upon needs and past experience. The frequency of haul road cleaning/regrading and repairing was mostly mine specific. Cleaning and regrading at some mines was done daily and major repair work was performed after haul road failure. The frequency of measures taken for dust suppression, as expected, increased during summer and in some cases was as high as once per shift. Mines surveyed by Monenco (1989) also removed snow from haul roads in winter to improve traction. Three mines surveyed by Monenco (1989) and one mine surveyed in this study reported use of preventive maintenance for haul roads.

## 1.8 Evolution of Haul Road Design at Syncrude

Syncrude Canada Limited operates a number of oil sand mines near Fort McMurray, Alberta, Canada. Syncrude has implemented a number of design modifications for haul roads to account for the increases in haul truck payload capacities from 170t in 1988 to 360t in 1999 (Cameron et al. 1999). In the 1980’s, road designs were based on the California Bearing Ratio (CBR) method (Wills 1989). This method yielded satisfactory design until the introduction of larger 240t trucks in 1995 (Van Wieren & Anderson 1990, Cameron & Lewko 1996, Cameron et al. 1996a, b). The larger haul trucks resulted in failure of roads designed for 170t trucks, such as heavy rutting and structural breakdown of the haul road cross-section (Cameron et al. 1996a). A new design method based on deflection (strain) of various layers was developed during 1995-96 (Cameron et al. 1996a, b). Deflections at the surface and at the sub-grade were predicted for various truck sizes (170t – 340t). The haul road design was modified such that the vertical deflection at the road surface is less than 8.3mm for 240t trucks and 4.3mm at the sub-grade (Cameron & Lewko 1996). With the introduction of larger trucks (320t in 1997 and 360t in 1999), the road design was further modified to meet the same deflection criteria (Cameron & Lewko 1997a, 1997b, 1998, 1999a, 1999b).

### 1.8.1 Layer Thickness

The haul roads were generally constructed with three distinct materials. Sand was used as the sub-base, while pit run gravel and crushed gravel were used as the base layer and the surface, respectively (Wills 1989). The thickness of each layer was determined using the 8mm deflection criterion but was later modified based on past experience and material availability. Figure 1-1 shows layer thicknesses for various truck sizes from 1988 to 2000 (Cameron et al. 1999). Larger trucks required a thicker gravel layer for a combined running (surface) and base layer but the sand layer thickness for the sub-base remained the same as that for smaller trucks. This is because for large trucks, high stress travels deeper in the haul road cross-section requiring thicker, stiffer material (gravel) to keep the deflection (strain) at the road surface within the design limit (8mm).

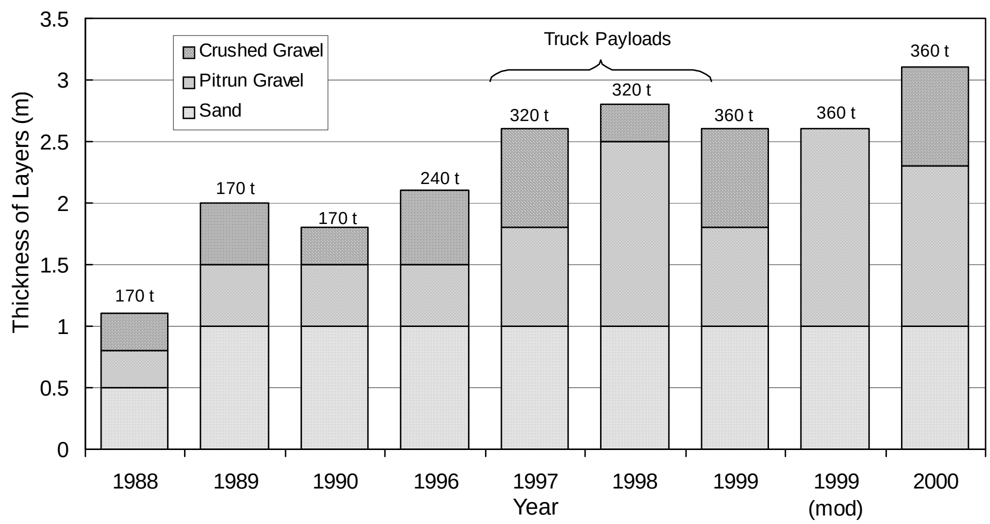


Figure 1-1 Change of haul road layer thicknesses with introduction of larger haul trucks.

### 1.8.2 Haul Road Geometry

Haul road width, quite understandably, increased with the increase in the truck size. Table 1-11 shows the haul road width for various truck sizes (Cameron et al. 1999). The haul roads are designed to be 3.5 to 4 times the width of the largest truck using the road. This rule of thumb is intended to provide adequate passing clearance between trucks. More recently, there has been discussion about establishing criteria for what constitutes a safe passing distance. It has been suggested that a fixed minimum clearance distance between trucks is needed because the distance should not be only a function of truck width. Further research is needed in this area. Nevertheless, it is interesting to note that the recommended road to truck width ratio for Syncrude mine roads has increased over time although a fixed-distance logic suggests it should decrease.

Table 1-11 Haul road widths at Syncrude Canada Ltd.

| Haul truck capacity (ton) | Truck Width (m) | Haul road width (m) | Ratio of road to truck width |
|---|---|---|---|
| 170 | 7.10 | 25 | 3.5 |
| 240 | 7.60 | 30 | 3.9 |
| 320 | 8.45 | 32 | 3.8 |
| 360 | 9.15 | 36.8 | 4.0 |

Due to increase in the truck tire size, the height of safety berms was increased from 2.0m for 240t trucks to 2.9m for 360t trucks. The height of the safety berm is usually related to the tire diameter and larger trucks use bigger tires. The recommended berm height/tire diameter is about 3/4 with all berms being greater than 1 m high regardless of tire size.

Other elements of haul road geometry such as slope of sides, ditch depth, and lift thickness have remained more or less constant over the years (Cameron et al. 1999). Figure 1-2 and Figure 1-3 show geometrical elements of haul roads for 240t and 360t trucks respectively. For most materials, the sides of the roads were kept at a slope of 3H:1V. Each lift was crowned 2% towards the centre of the road to provide adequate surface drainage. The depth of the ditch was maintained at 0.5m below the sub-base.

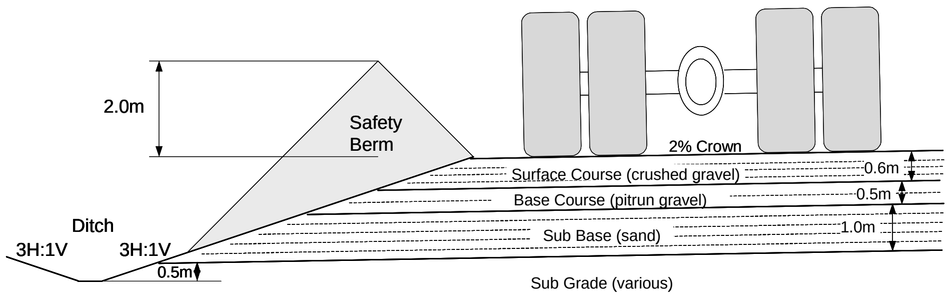


Figure 1-2 Partial haul road cross-section for a 240t truck.

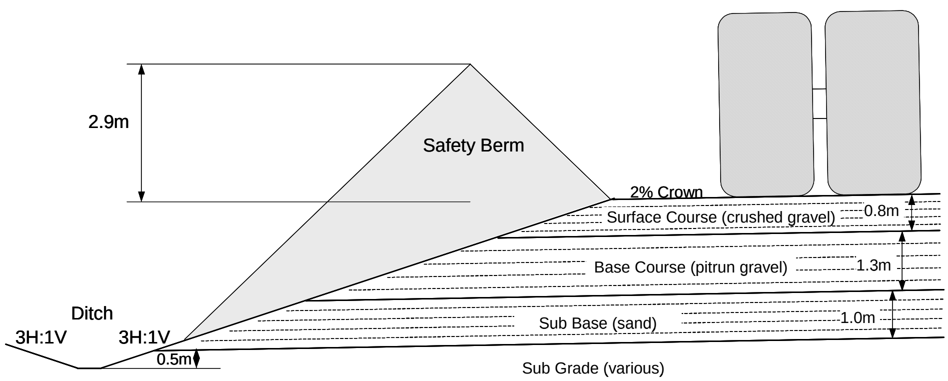


Figure 1-3 Partial haul road cross-section for a 360t truck.

### 1.8.3 Construction Techniques

Haul roads were constructed with haul trucks to deliver (and compact) materials, graders and dozers to spread the material in appropriate lift heights, and smooth drum vibratory compactors. Haul roads were not constructed on frozen sub-grades or during temperatures below 0°C. The moisture contents of the construction materials were kept at –2% to –4% of the optimum moisture content (Cameron & Lewko 1999a).

In 1997, with the introduction of 320t trucks, sub-grade preparation was made more stringent from 150mm rut-and-roll proof surface to 50mm rut-and-roll proof surface to allow road construction using 240t trucks. Note, a 50mm rut-and-roll means that when a loaded truck of specified size travels over the prepared surface, the combined depth of ‘rut’ produced by the tire and the surface heave or ‘roll’ around the tire is less than 50mm.

Some sub-grades required a cut and fill operation. Clay or interburden was placed and compacted with 200t or larger trucks in such a manner that it met the final rut and roll criterion for the sub-grade (Cameron & Lewko 1999a). This was achieved by compacting these weak materials well below the optimum water content, in 1m to 2m thick lifts, just prior to road construction. The remainder of the road must be built on top of these materials soon after they are compacted because moisture conditions change over time and the sub-grade can quickly degrade. Furthermore, if trucks continue to run over the unprotected sub-grade it can become heavily rutted.

The roads are typically constructed using large mining trucks to both deliver and compact the construction materials. It is very difficult to knock down piles of sand or pit run gravel from a 240t hauler, even with the new Caterpillar 24-H graders. Therefore, these materials are spread with a minimum D10 dozer.

The sub-base was compacted to a density of 95% Standard Proctor by a smooth drum vibratory roller. Sand was placed in 0.35m thick lifts before compaction (Cameron & Lewko 1999a). The base layer was constructed from pit run gravel, spread in 0.5 m thick lifts by D10, D11 or equivalent dozers. The material was compacted to 98% Standard Proctor by using 4 to 6 passes of a smooth drum vibratory roller plus 4 to 6 passes with loaded 200t trucks (Cameron & Lewko 1999a).

The surface layer was usually constructed from crushed gravel, placed in 0.25m lifts, spread by a grader, and compacted to 98% Standard Proctor by smooth drum vibratory roller (Cameron & Lewko 1999a). The compaction was proposed to be increased to 100% Standard Proctor in the year 2000 (Cameron et al. 1999).

## 1.9 Summary

There has been a marked increase in the size of the trucks used over the last decade. Some mines use trucks of payload capacity as high as 360mt or larger. Consequentially, geometrical elements of haul roads, such as width, have been enlarged to accommodate larger trucks. Larger trucks also means greater load on the road but little design work has been done by various mines (except Syncrude Canada Ltd.) to account for larger truck sizes. Haul road construction and maintenance procedures followed by various mines are based on past experience and trial and error methods.

# 2 HAUL ROAD PLANNING AND ALIGNMENT

## 2.1 General

Various classifications for haul roads exist. Primary or permanent roads are used for longer than six months or are intended for an approved post-mining land use. Ancillary or temporary roads are roads not classified as primary and may be used for exploration access, for in-pit haulage, and for pit access. Other definitions refer to three classes of roads: longer-lived haul roads, pit access roads, and in-pit roads. Only the last group may be constructed from indigenous materials without a running surface made from gravel or other resistant material.

Mine design involves determination of road parameters such as grade, traffic layout, curves, intersections, and switchbacks. The choice of grade may affect access to the ore body, exposing more minerals for extraction and affecting stripping ratios.

As reiterated by Kaufman and Ault (1977), geometric elements of haul roads should be designed to provide safe, efficient travel at normal operating speeds. The ability of the vehicle operator to see ahead a distance within which he can stop the vehicle is a primary consideration. Vehicle stopping distance is one component that must be evaluated for each type of vehicle in the haulage fleet to allow the designer to establish horizontal and vertical road alignment. Associated with the vehicle stopping distance is the operator "sight distance". It is imperative that everywhere along the road alignment the sight distances be sufficient to enable a vehicle travelling at the posted speed to stop before reaching an obstruction or hazardous situation on the road ahead. On vertical curves, the sight distance is limited by the road surface at the crest. On horizontal curves, steep rock cuts, trees, structures, etc. limit sight distance. The distance measured from the driver's eye to the hazard ahead must always be equal to or greater than the distance required to safely stop the vehicle.

## 2.2 Key Road Planning and Alignment Factors

**Stopping Distances**

Stopping distances must be calculated for each vehicle and the alignment of the road adjusted to the vehicle with the longest stopping distance.

**Sight Distances**

The sight distance that a driver has must be equal to or greater than the stopping distance of the vehicle. Both horizontal and vertical curves must be planned with this criterion.

**Road Widths and Cross Slopes**

The width of the travelled portion of a haul road is usually calculated as a multiple of the width of the widest vehicle that regularly travels it. In most cases, a straight stretch of road will be 3 to 4 times the width of the widest heavy hauler. On corners, the width will usually be designed wider than the straight stretch to allow for overhang of vehicle on the corner.

Cross slopes should be approximately 1:25 to ensure proper drainage off the road.

**Curves and Super-elevation**

Horizontal curves should be designed to ensure that all the vehicles can safely negotiate the curve at a given speed, taking into account sight distance and minimum turning radius.

Super-elevation of the curve is required to reduce the centrifugal forces on the truck when it negotiates the corner.

**Super-elevation Runout**

When approaching a super-elevation corner from a straight stretch, there must be a gradual change from level to super-elevation to allow the driver to safely manoeuvre the truck through the curve.

**Maximum and Sustained Grade**

Grade (steepness) of roads is a function of safety and economics. In most cases, grades will vary between 0 and 12% on long hauls and may approach 20% on short hauls. However, most haul road grades in mines will have a grade between 6% and 10%. It is usually best to design haulage with a long sustained grade rather than a combination of steeper and flatter sections.

**Intersections**

Intersections should be made as flat as possible and should be avoided at the top of a ramp.

## 2.3 Haul Truck Stopping Distance

Specifications for brake performance provided by most truck manufacturers are generally limited to an illustration of the speed that can be maintained on a downgrade by use of dynamic or hydraulic retardation through the drive components. Although this is an efficient method of controlling descent speed, it does not replace effective service brakes. Should the retardation system fail, wheel brakes become the second line of defence to prevent vehicle runaway.

Recognising the need for effective brake performance standards, the Society of Automotive Engineers (SAE) developed test procedures and minimum stopping distance design criteria for different weight categories of large, off-highway trucks. It is uncertain how brake performance may vary with changes in grade, road surface conditions, initial speed, or, indeed, with brake system wear or contamination with dust, oil, water, etc.

To assess stopping distances for different grades and speeds, Kaufman and Ault (1977) developed an empirical formula based on the SAE stopping distance limitations:

$$SD = \tfrac{1}{2} g t^2 \sin\theta + V_o t + \left[ \frac{g t \sin\theta + V_o}{2g\left(U_{\min} - \sin\theta\right)} \right]^2 \qquad \text{Equation (1)}$$

Where:

| | | |
|---|---|---|
| $SD$ | = | stopping distance (m) |
| $g$ | = | gravitational acceleration (9.81 $m/s^2$) |
| $t$ | = | elapsed time between driver's perception of the need to stop and the actual occurrence of frictional contact at the wheel brakes (s) |
| $\theta$ | = | angle of descent (degrees) |

| | | |
|---|---|---|
| $U_{min}$ | = | coefficient of friction at the tire-road contact area |
| $V_o$ | = | vehicle speed at time of perception |

The factor $t$ is actually composed of two separate time intervals, $t_1$ and $t_2$. Component $t_1$ is the elapsed time for brake reaction due to pressure build-up in the brake system after the brake pedal is depressed and the brake mechanism is actuated to effectively exert a retarding force on the wheels. A typical value of brake reaction time suggested by SAE for a haul truck (180mt GVW) is 4.5s. The brake reaction time may be higher for the much larger trucks currently being used.

The second component of $t$, designated $t_2$, is driver reaction time, i.e. the time between driver perception of a hazard and when his foot actually begins to depress the brake pedal. A reasonable value of $t_2$ is 1.5s.

The factor $U_{min}$ was evaluated from the following expression:

$$U_{min} = \frac{V^2}{2gS} \qquad \text{Equation (2)}$$

Where:

| | | |
|---|---|---|
| $V$ | = | SAE test velocity of 8.94m/s (32.2km/hr) |
| $g$ | = | $9.81 m/s^2$ |
| $S$ | = | stopping distance computed by subtracting (8.94 x $t_1$) from the SAE recommended stopping distance |

Substitution of the various SAE stopping distances and $t_1$ factors for each weight category into Equation 2 yielded an average minimum achievable coefficient of friction, $U_{min}$, of 0.3 and a corresponding vehicular deceleration of about $2.94 m/s^2$.

Based on Equations 1 and 2, stopping distance curves can be developed for different grades and speeds. However, these formulae do not account for brake fade due to heat build-up which constant brake application may induce. Kaufman and Ault (1977) note that these equations are not based on the results of actual field tests, and can only be used as a rough guideline in the preliminary planning stage of road design. Before actual road layout begins, the haul truck manufacturer should be contacted to verify the service brake performance capabilities of their trucks without assistance from dynamic or hydraulic retardation systems.

Trial service brake stopping tests for a Caterpillar 785 haul truck (GVW = 230mt) on a 9% downgrade indicated a stopping distance of 67m from an initial speed of about 60km/hr (Holman 1989). The tests were conducted in accordance with SAE J1473 procedures, which require the stopping distances set out in Table 2-1 for this vehicle weight on a 9% grade.

Table 2-1 Trial service brake stopping tests for a Caterpillar 785 haul truck (Holman 1989).

| Speed (km/hr) | Stopping distance (m) |
|---|---|
| 15 | 10 |
| 35 | 50 |
| 50 | 100 |
| 60 | 150 |
| 65 | 170 |

MacMillan (1989) reports brake-stopping tests on the 830E Haulpak (GVW = 386mt) wherein a stopping distance of 84m was measured on a 10.4% downgrade. More recent brake test results for the larger haul trucks could not be found in the published literature.

Haul truck brake performance curves are available for most of the Caterpillar trucks (see Figure 8-3 and Figure 8-4 for examples). These curves can be used to determine the speed that can be maintained when the truck is descending a grade with retarder applied.

## 2.4 Sight Distance and Vertical Curves

Vertical alignment in road design requires judicious selection of grades and vertical curves that permit adequate stopping and sight distances on all segments of the haul road. The relationship between operator sight distance and vehicle stopping distance is illustrated on Figure 2-1 for safe and unsafe conditions.

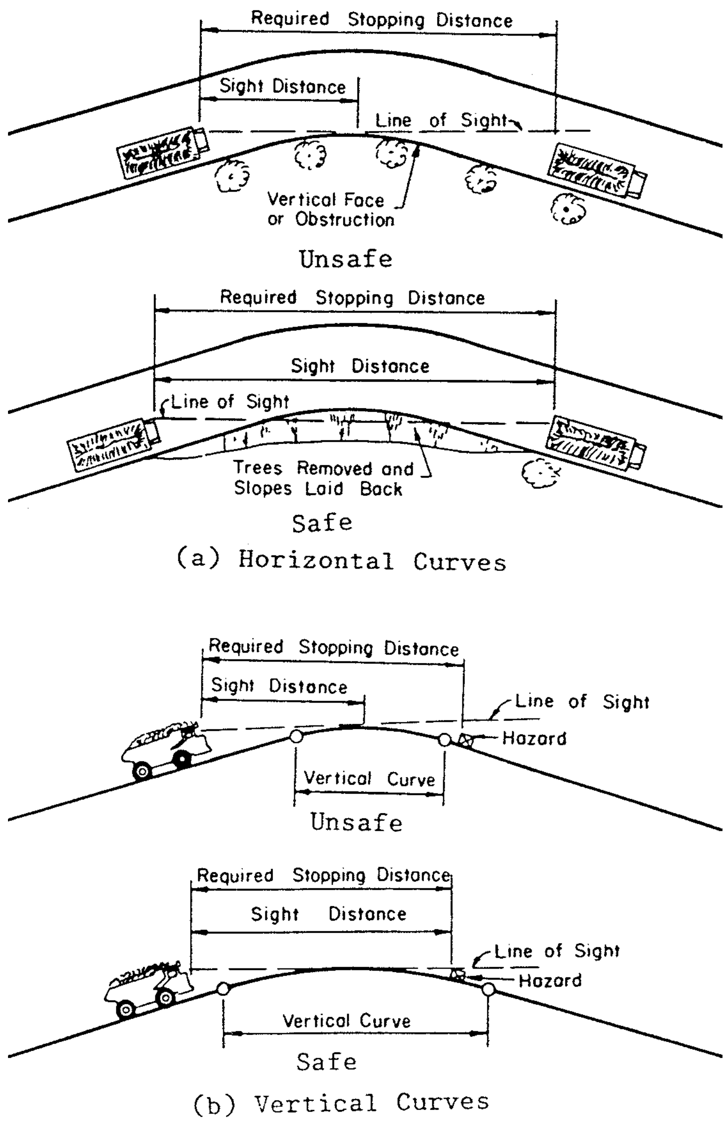


Figure 2-1 Sight distances for horizontal and vertical curves (after Monenco 1989).

Vertical curves are used to provide a smooth transition from one road grade to another. Lengths of vertical curves should be adequate to drive comfortably and provide ample sight distances at the designed vehicle speed. Monenco (1989) recommend the following expressions for computing curve lengths:

For *S* greater than *L:*

$$L = \frac{2S - 200 \cdot \left(\sqrt{h_1} + \sqrt{h_2}\right)^2}{A} \qquad \text{Equation (3)}$$

For *S* less than *L:*

$$L = \frac{AS^2}{100\left(\sqrt{2h_1} + \sqrt{2h_2}\right)^2} \qquad \text{Equation (4)}$$

Where:

| | | |
|---|---|---|
| *L* | = | Length of vertical curve (m) |
| *S* | = | Attainable vehicle stopping distance (m) |
| *A* | = | Algebraic difference in grades (%) |
| $h_1$ | = | Height of driver's eye above ground (m) |
| $h_2$ | = | Height of object above road surface (m) |

The height of object above the road surface should be taken as 0.15m to cover such possibilities as a prostrate figure, an animal or dropped gear on the road surface.

Generally, curve lengths greater than the computed minimum are desirable as they result in longer sight distances. Excessive lengths, however, can result in long, relatively flat sections that may lead to soft spots or potholes unless adequate drainage is provided. In any event, vertical curve lengths less than 30m should be avoided.

## 2.5 Road Width

The width of haul roads on both straight and curved sections must be adequate to permit safe vehicle manoeuvrability and maintain road continuity. Since the size of equipment that travels on haul roads varies significantly from mine to mine, vehicle size rather than vehicle type or gross vehicle weight are best used to define road width requirements. In the past, for straight road segments, it was recommended that each lane of travel should provide clearance on each side of the vehicle equal to one-half of the width of the widest vehicle in use (AASHO 1965). This is illustrated in Figure 2-2. For multiple lane roads, the clearance allocation between vehicles in adjacent lanes is generally shared. With the much larger and wider truck in use today, the guidelines regarding appropriate clearance may need to be reviewed.

Roads that are too narrow can drastically reduce tire life by forcing the truck operator to run on the berm when passing another vehicle. This results in sidewall damage, uneven wear, and cuts. This is a particular problem when an operator adds new larger trucks to an existing fleet but does not change the road layout to accommodate the wider trucks.

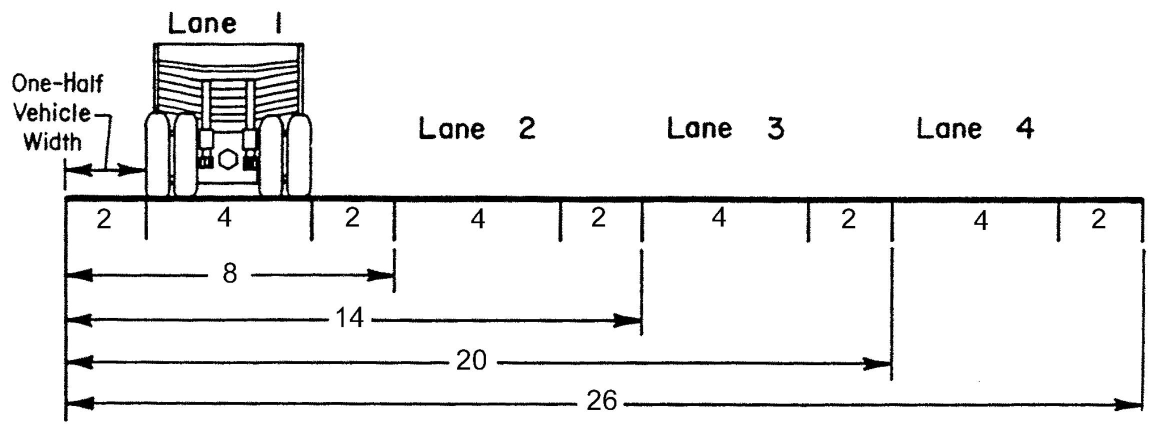


Figure 2-2 Relation between road width and number of traffic lanes with distances in metres for a 4m wide truck (after Monenco 1989).

The minimum width of running surface for the straight sections of single and multi-lane roads can thus be determined from the following expression:

$$W = (1.5L + 0.5)X \qquad \text{Equation (5)}$$

Where:

| | | |
|---|---|---|
| *W* | = | width of running surface (m) |
| *L* | = | number of lanes |
| *X* | = | vehicle width (m) |

For example, the minimum road width for a CAT 797 truck, which is 9.15m wide, running on a two-lane road is 32m.

Additional road width in excess of the minimum determined from Equation 5 might be required locally along the road alignment, for example:

- to accommodate equipment larger than the primary road users, such as shovels or draglines,
- to allow sufficient room for vehicles to pass on single lane roads, and
- if, on single lane roads, the sight distance is less than the stopping distance, sufficient space must be provided for moving vehicles to avoid collision with stalled or slow-moving vehicles.

Switchbacks or other areas on haul roads requiring sharp curves must be designed to take into consideration the minimum turning radius of the haul trucks. Typical minimum turning radii for vehicles in the different weight categories, along with minimum U-turn radii for Terex and Kress bottom dumps, are included in Table 8-3.

A wider road is required on curves to account for the overhang occurring at the vehicle front and rear. The procedure for determining road width on curves to account for vehicle overhang, lateral clearance between passing haul trucks and extra width allowance to accommodate difficult driving conditions on curves is shown on Figure 2-3. Since curve widths vary for vehicles in each weight category and for different curve radii, Kaufman and Ault (1977) recommend the widths given in Table 2-2 for single unit and articulated haul trucks, respectively. This table should be used as a guideline to establish the minimum width of road around horizontal curves.

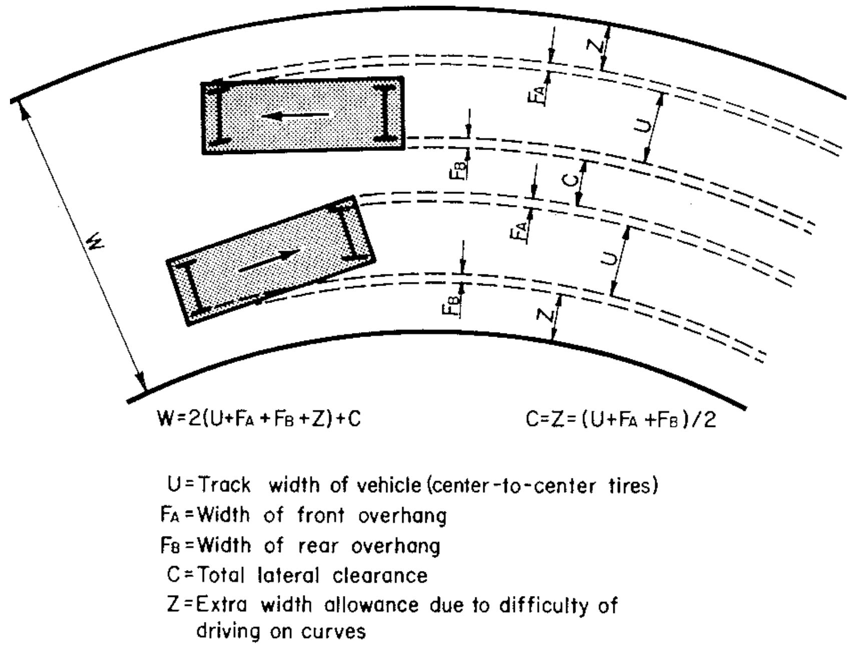


Figure 2-3 Procedure for computing road width on horizontal curves (Monenco 1989).

Table 2-2 Design widths (in metres) for horizontal curves for a haul truck with payload of 180mt (after Kaufman & Ault 1977).

| Curve radius on inner edge of pavement (m) | One-lane road (m) | Two-lane road (m) | Three-lane road (m) | Four-lane road (m) |
|---|---|---|---|---|
| | | Single unit haul truck | | |
| Minimum | 21.0 | 36.9 | 52.8 | 68.7 |
| 7.5 | 20.4 | 35.7 | 51.0 | 66.3 |
| 15 | 18.9 | 33.0 | 47.4 | 61.5 |
| 30 | 17.7 | 30.9 | 44.1 | 57.6 |
| 45 | 17.4 | 30.3 | 43.5 | 56.4 |
| 60 | 17.1 | 30.3 | 43.2 | 56.1 |
| Tangent | 16.8 | 29.4 | 42.0 | 54.6 |
| | | Articulated haul truck | | |
| 7.5 | 25.8 | 45.3 | 64.5 | 84.0 |
| 15 | 21.3 | 37.2 | 53.1 | 69.3 |
| 30 | 17.4 | 30.3 | 43.2 | 56.1 |
| 45 | 15.6 | 27.3 | 39.0 | 50.4 |
| 60 | 14.7 | 25.5 | 36.6 | 47.4 |
| Tangent | 12.3 | 21.6 | 30.9 | 39.9 |

## 2.6 Curves and Switchbacks

Horizontal haul road alignment addresses the required width and super-elevation of the road to enable vehicles to safely negotiate around curves at a given speed taking into account sight distance and minimum vehicle turning radius. The cost implications of physical constraints to construction, such as quantity of rock excavation necessary, must also be considered in laying out the curve. For example, to construct a road around a prominent rock nose in mountainous terrain, the designer has to weigh the cost of rock excavation for a large radius curve that can be negotiated safely at, say 40km/hr, against a tighter curve with minimal rock excavation but which requires vehicles to slow to 20km/hr, thereby increasing vehicle cycle time and penalizing productivity during the life of the road.

Curve and switchback design should include consideration of truck performance. Haul roads designed for constant speed will allow trucks to perform to their potential. The truck performance may have a greater influence on mining costs than the initial road construction costs. Poorly designed curves that slow the cycle time can add thousands of dollars in haulage cost each day.

Equation 6 is a generally accepted formula for curve design. This formula considers the speed of the truck, friction on the road surface, super-elevation and curve radius. The formula tries to balance the outward centrifugal forces with siding resistance plus the inward component of force from the vehicle weight and super-elevation. The maximum potential speed of the truck is a function of the grade plus rolling resistance. For curves on roads where the grade is greater than zero, design the curve radius for the fastest truck, which is usually the truck going downhill.

$$R = \frac{V^2}{127(e + f)} \qquad \text{Equation (6)}$$

Where:

| | | |
|---|---|---|
| $R$ | = | curve radius (m) |
| $V$ | = | vehicle speed (km/hr) |
| $e$ | = | super-elevation (m/m) |
| $f$ | = | coefficient of friction between tires and road surface (friction factor or traction dimensionless). |

For example, a truck travelling at 60km/hr on a road surface with a friction factor of 20% and a 5% super-elevation requires a curve radius of about 113m.

Design the road for constant speeds if possible. This leads to consistent truck performance with minimal slowdowns. Increasing grade through a curve will slow a truck on both haul and return trips and puts more wear and tear on components. Aim to place curves where the grade is flatter to help maintain a more constant truck speed and reduced wear and tear.

Use larger curve radii whenever possible. A larger curve radius allows higher safe road speed and reduced traffic congestion, as well as less wear and tear on both the road and the hauler. Sharp curves or switchbacks are sometimes necessary, but they increase haulage costs. The dual tires on drive axles are especially prone to wear going around tight curves. A switchback with an inside depression dug from tire slip is common. This causes loaded and empty trucks to slow down, reducing production. Extra road maintenance will also be required, further adding to road congestion. Sharp curves also lead to reduced visibility or sight distance.

Do not forget to consider both directions when designing a curve. The design must account for the empty truck, which generally travels faster.

It is emphasized, however, that operational safety should not be compromised and that any relaxation of specifications to mitigate construction costs should be accompanied by a corresponding reduction in operating speed.

## 2.7 Super-Elevation

Negotiating curves can generate high lateral tire forces. These forces contribute to high tire wear and ply separation. Super-elevating the curve helps eliminate these forces. Ideally, tire wear would be reduced and steering would be effortless if road super-elevation was just equal to the vehicle weight component. There is a practical limit to which a road can be super elevated since high cross-slopes around curves can, for slow moving vehicles, cause higher loads on the inside wheels, increased tire wear, potential bending stresses in the vehicle frame and, on ice covered surfaces, vehicle sliding down the cross-slope.

The amount of super-elevation depends on the curve radius and truck speed. Table 2-3 is a guide for providing the super-elevation necessary to eliminate lateral forces. Super-elevated curves present a danger when the road surface is slippery. Unless the proper speed is maintained, a vehicle may slide off of the lower edge of the roadway. For this reason, super-elevation over 10% should not be used. Super-elevated curves should be maintained in good tractive conditions. The values of super-elevations listed in Table 2-3 over-estimate the practical super-elevations that are needed in practice.

Table 2-3 Curve super-elevation (in % grade) to provide no lateral tire force (Caterpillar 1999).

| Turn radius | | Vehicle speed | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| (m) | (ft) | 16km/hr 10mph | 24km/hr 15mph | 32km/hr 20mph | 40km/hr 25mph | 48km/hr 30mph | 56km/hr 35mph | 64km/hr 40mph | 72km/hr 45mph |
| 15.2 | 50 | 13% | --- | --- | --- | --- | --- | --- | --- |
| 30.5 | 100 | 7% | 15% | --- | --- | --- | --- | --- | --- |
| 45.7 | 150 | 4% | 10% | --- | --- | --- | --- | --- | --- |
| 61.0 | 200 | 3% | 8% | 13% | --- | --- | --- | --- | --- |
| 91.5 | 300 | 2% | 5% | 9% | 14% | --- | --- | --- | --- |
| 152.4 | 500 | 1% | 3% | 5% | 8% | 12% | 16% | --- | --- |
| 213.4 | 700 | 1% | 2% | 4% | 6% | 9% | 12% | 15% | --- |
| 304.9 | 1000 | 1% | 2% | 3% | 4% | 6% | 8% | 11% | 14% |

Another approach to designing super-elevated curves is to determine the safe speed for negotiating a turn at a certain lateral tire force. In general, a 20% lateral coefficient of traction is safe for all but slippery conditions. Table 2-4 shows the maximum speed with various super-elevations to maintain a 20% lateral coefficient of traction. A transition “zone” may be necessary at higher speeds when entering or departing from a super-elevated turn.

Table 2-4 Safe speeds (km/hr) for negotiating a curve while maintaining a lateral coefficient of traction less than 0.2 (Caterpillar 1999).

| Radius (m) | 0% Flat | 5% Super-elevation | 10% Super-elevation |
|---|---|---|---|
| 7.6 | 14 | 16 | 17 |
| 15.2 | 20 | 22 | 24 |
| 30.5 | 28 | 31 | 34 |
| 45.7 | 34 | 38 | 42 |
| 61.0 | 39 | 44 | 48 |
| 91.5 | 48 | 54 | 59 |
| 152.5 | 62 | 70 | 76 |
| 213.5 | 74 | --- | --- |

Field trials have demonstrated (AASHO 1965) that, for short-radius curves, the side friction factor increases as vehicle speed decreases, and thus the required super-elevation computed as per Equation 6 is small and within the range of cross-slopes generally used for surface drainage. This information, along with the fact that short curves afford little opportunity for providing super-elevation and run out, lead to the formulation of the recommended super-elevations for different speeds and curve radii given in Table 2-5.

Table 2-5 Recommended super-elevations for horizontal curves (after Kaufman & Ault 1977).

| Radius of | Vehicle speed (km/hr) | | | | |
|---|---|---|---|---|---|
| curve (m) | 24 | 32 | 40 | 48 | >56 |
| 15 | 4% | | | | |
| 30 | 4% | 4% | | | |
| 45 | 4% | 4% | 5% | | |
| 75 | 4% | 4% | 4% | 6% | |
| 90 | 4% | 4% | 4% | 5% | 6% |
| 180 | 4% | 4% | 4% | 4% | 5% |
| 300 | 4% | 4% | 4% | 4% | 4% |

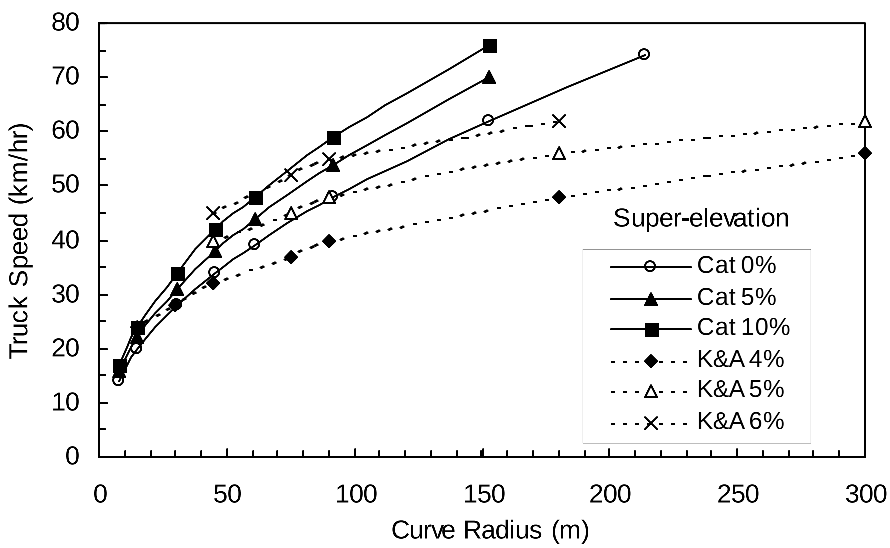


Figure 2-4 Road super-elevation versus vehicle speed based on data in Table 2-4 and Table 2-5.

The data in Table 2-4 and Table 2-5 are plotted together on Figure 2-4. This figure shows that Kaufman and Ault (1977) and Caterpillar (1999) give essentially the same recommendations for super-elevations for tight curves and slow moving trucks. The two curves for a super-elevation of 5% show that the Caterpillar recommended curve radii are smaller than those from Kaufman and Ault (for truck speeds exceeding 40km/hr).

Ideally, traffic on a wide, high-speed haul road may benefit from separate super-elevation curve profiles within each lane, thus allowing traffic in both directions to maintain speed without stressing the tires, casting off rocks, or skidding sideways.

Syncrude Canada Ltd. does not use super-elevation exceeding 6% on any roads. This is consistent with other mines where super-elevation seldom exceeds 4 to 5%. This minimizes erosion of the running surface during rainy or wet operating conditions. A practical limitation to the maximum allowable super-elevation means that reduced speed is needed to minimize centrifugal side forces on tires in tight curves or large curve radii should be used when possible.

### 2.7.1 Super-Elevation Runout

The transition between a normal road cross-section and a super-elevation section should be gradual to assist the driver in manoeuvring the vehicle through the curve. Kaufman and Ault (1977) recommend that this portion of the road, termed the transition or run out length, be apportioned one-third to the curve and two-thirds to the tangent. Run out lengths vary with vehicle speed and total cross-slope change as shown in Table 2-6.

Table 2-6 Maximum cross-slope changes per 30m segment of road (after Kaufman & Ault 1977).

| Vehicle speed (km/hr) | Maximum change in cross-slope per 30m of road length (%) |
|---|---|
| 16 | 8 |
| 24 | 8 |
| 32 | 8 |
| 40 | 7 |
| 48 | 6 |
| 56 & above | 5 |

The use of this tabulation can best be illustrated by an example. Suppose a vehicle is travelling at 56km/hr on a straight road with a cross-slope of 4% to the right. It encounters a curve to the left with a superelevation of 6% to the left, thus the total change in cross-slope is (4+6) or 10%. For 56km/hr, the recommended change in cross-slope is 5% thus the total runout length should be (10/5) x 30 = 60m. One third of this length, 20m should be fitted to each end of the curve and the remainder, 40m applied to each tangent at the beginning and end of the curve. A smooth spiral transition section not only allows vehicles to negotiate curves more easily but also minimizes twist on the vehicle chassis.

To ensure roads are constructed and maintained with smooth run out sections, thus minimizing the potential for metal fatigue from frame twist, onboard vehicle monitoring systems can be used with strain gauges to directly measure frame twist. A practical apparatus has been developed to directly measure induced twist as the road is travelled (Deslandes & Dickerson 1989). The device consists of a trailer, which is coupled to a haul truck through a rigid joint (Hooks joint). The track of the trailer and the effective wheel base between the rear axle of the truck and the trailer axle are adjustable to allow pre-setting and matching with those of the truck being used. Trailer tires are sized to match the truck tires. By such an arrangement, the angular distortions between the rear axle and trailer axle mimic those induced in the truck frame by twist of the truck tire–road surface contact points. Twist is resolved at a rotating joint located on the trailer drawbar and a direct measure of twist is provided on a recorder mounted in the driver's cab. A digital pulse indicator installed in one trailer wheel is used to increment the recorder to make the chart distance proportional to truck travel distance. By installing numerous strain gauges at crucial points on the truck frame, Monenco (1989) were able to record speed, twist and strain, and hence correlate frame response to twist measurements accumulated by the test trailer. They concluded that very good correlation between measured twist and frame strain was obtained. Since the trailer is of simple construction, it can provide results in real time, it does not require complex computer processing of data, and it causes minimal disruption of normal mine operations.

## 2.8 Optimal Grades

Optimizing truck performance depends on selecting the appropriate grade, especially when lots of vertical rise is encountered. Choosing the best slope requires examination of haul road geometry and truck performance on grade. The cycle time of the truck is the basic performance indicator to need to determine the optimum grade, because cycle time is a direct indicator of productivity. Time also includes a measure of the fuel consumption.

A shorter distance generally provides shorter travel time. However, in a mine, it is often necessary to also consider the effect of vertical rise. The distance travelled on grade varies with the vertical rise needed and the slope of the road. For example, in order to climb 100m vertically, a truck must travel 5km on a 2% grade or 1km on a 10% grade.

Distance, truck performance, GVW, grade resistance, and rolling resistance can be used to determine the time a truck will take to ascend a grade. Truck performance specifications are often presented as rimpull-speed curves (e.g., Figure 8-1 or Figure 8-2). These curves show how fast the truck travels under a given set of conditions and reflect the power output of the vehicle. Since most engines are rated at a certain horsepower and their output remains relatively constant under load, a truck goes faster under easier conditions and slower under tough conditions.

To determine truck speed from rimpull curves, calculate rimpull based on GVW and total resistance. When climbing, total resistance is equal to grade resistance plus rolling resistance. Once the required rimpull is determined, the speed can be read from the performance specification. The steady state speed on grade for a given truck varies with GVW and resistance (rolling and/or grade). The travel time is simply given by the distance divided by the truck speed.

In real mining situations, the GVW will likely vary because the shovel cannot place the same weight of material into the truck each trip. Therefore, variations in GVW should also be considered when designing the grade.

To gain a vertical rise a steeper grade typically gives the fastest cycle time and least fuel consumption. Steeper ramps also impact the mine plan, allowing more ore to be uncovered for a given pushback.

Maximum practical grades are determined not only by terrain characteristics and consideration of haul truck productivity but also by safe vehicle stopping distances (Figure 2-1). If grades are steep, haul trucks have to decrease speed on descent to ensure safe stopping distances and ascending equipment requires frequent gear reduction and consequent speed losses. Such changes in velocity result in lost production time, additional fuel consumption, increased mechanical wear and higher maintenance costs. The road design must also balance the projected savings of enhanced productivity on flatter grades against the capital cost of excavation and embankment fill to achieve these flatter grades.

The impact of grade on vehicle performance when ascending a grade can be demonstrated by inspection of the typical performance chart (Figure 8-1 or Figure 8-2). For example, Figure 2-5 shows the uphill haul times for a CAT 793C with a GVW averaging 350,000kg for a vertical rise of 100m (based on Figure 8-1). This figure takes into account that a steeper grade results in a shorter haul distance. Grade resistance plus rolling resistance gives the total grade. The figure clearly shows that although a truck travels fastest on the shallower grades, the longer distance needed to gain the elevation takes more time. The figure shows minimum travel times occur for grades that range between 8% and 14% depending on the rolling resistance. Grades beyond roughly 10% result in fairly steep climbs, which would significantly increase power train loads and wear and tear on the truck. The slight increase in travel time when adopting a grade of about 9% ±2% is the best choice and can be justified in terms of reduced operating cost for the truck.

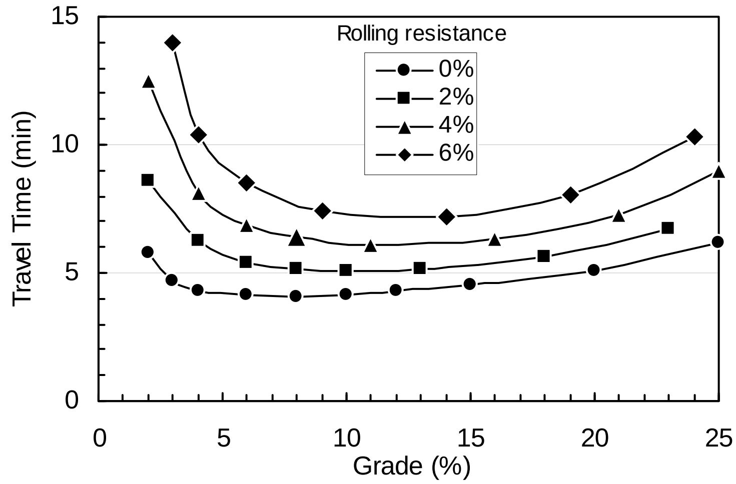


Figure 2-5 Uphill haul time for a CAT 793C with GVW = 350,000kg for a vertical rise of 100m operating at highest speed as a function of total grade resistance.

It is apparent that grades less than 10% to 15% allow significantly higher uphill speed. Thus, haulage cycle times, fuel consumption, and stress on mechanical components, which results in increased maintenance, can be minimized to some extent by limiting the grade severity.

The rimpull-speed curves can also be used to balance combinations of GVW and total resistance so that the rimpull remains constant. For example, a CAT 797 (Figure 8-2) operating at a constant rimpull of 30,000kg (and speed of 24km/hr) can operate at the following GVW and total resistance combinations: 315mt & 10%, 394mt & 8%, or 525mt & 6%. Within the range of likely GVW, an addition of 1% total resistance has the same effect on rimpull and truck speed as approximately 40 to 65mt of extra GVW, with the effect being more pronounced at lower grades.

The road design should not exclusively focus on the uphill-loaded performance of trucks, excluding downhill-empty time. While trucks spend more time going up and small improvements in this portion of the cycle can yield overall improvements of a larger nature, gains can also be made through appropriate design of the downhill portion. Downhill travel is governed by the truck's ability to control speed on a particular grade. The key factors affecting the retarding or braking performance of a truck are the required retarding force, energy dissipation capacity and net truck performance.

The required retarding force is a function of the GVW, grade assistance, and rolling resistance. When going downhill, the grade assists the truck to gain speed while the rolling resistance slows the truck. The net resistance in combination with the GVW determines the required retarding force to maintain constant speed while descending the grade.

Nearly all truck-retarding systems work by absorbing the mechanical energy required to slow and/or to maintain truck speed. This mechanical energy is converted into heat and rejected to the atmosphere via the cooling system. The energy dissipation capability of the truck retarding system determines the performance curve for retarding operation in a manner similar to rimpull curves for the uphill haul. The energy rejection capacity of a truck depends on the distance travelled, ambient temperature, altitude, and physical plant of the truck. Distance may affect performance in that a truck may not reach steady-state energy dissipation limits on shorter grades. This allows for either steeper grades or higher safe speeds when the grade is short. On long grades, steady state will be reached and a constant speed that is matched to the applicable conditions will result. Temperature and altitude affect the heat rejection capability due to their effect on the basic heat transfer process in the cooling system. In general, heat removal degrades as altitude and ambient temperature increase.

Significant improvements have been made in controlling downhill speed through hydraulic and dynamic retardation of drive components (Macmillan 1989, Holman 1989, and Johnson 1989). All retardation systems function by dissipating the energy developed during descent in the form of heat. In hydraulic systems, this is accomplished through water-cooled radiators; the dynamic method generally relies on air-cooled resistance banks. It is possible to overheat either system if the combination of grade and length is excessive.

In order for a truck to operate at its optimum efficiency, it is important to avoid temperature spikes. This can be achieved by allowing constant truck speed (constant grade) and eliminating stops and slowdowns.

Typical retarding performance charts for a CAT 793C truck are shown in Figure 8-3 and Figure 8-4. The downhill truck speed is based on input of the required retarding force, which in turn is based on GVW and effective grade. The truck speed can be used to determine travel times. Figure 2-6 shows the time needed to travel down grade to achieve a vertical drop of 100m. The minimum times depend on which gear the truck is using as well as effective grade and GVW. For the conditions assumed, Figure 2-6 shows that an empty truck takes about 1.4 minutes to drop 100m on a 8% grade (6% effective grade) when using the 6th gear. If the truck carried load such that the GVW was 350mt, then it would be required to gear down to 4th gear and would take 2.5 minutes to cover the same distance.

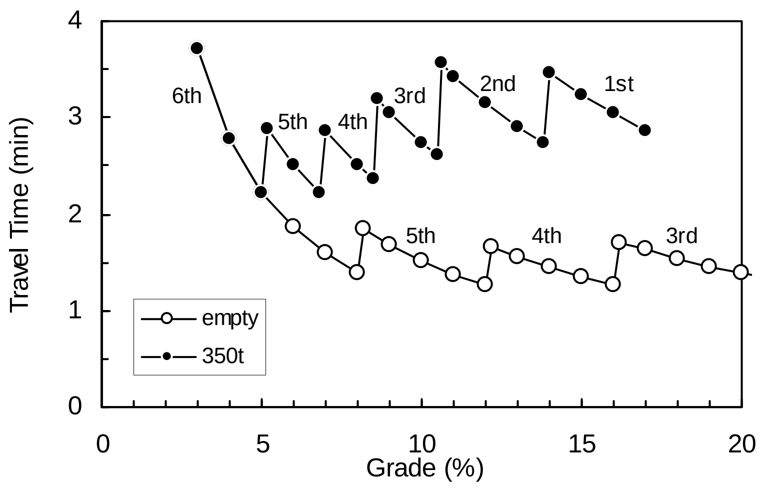


Figure 2-6 Downhill haul time on a continuous grade for a CAT 793C (158mt empty & 350mt full GVW) for a vertical drop of 100m operating at highest speed as a function of grade (with an assumed rolling resistance of 2%).

Figure 2-5 and Figure 2-6 can be combined to determine the return trip haul times for a truck. Assuming the rolling resistance is 2%, these two figures show that a minimum haul time per

100m elevation gain for a truck climbing loaded and returning empty occurs at grades of 8% and 12%. The cycle time (100m elevation change) is 6.6 minutes on 8% grade and 6.5 minutes on 12% grade. Given that the difference is small between these two cycle times and that wear and tear can be minimized when travelling on the lower grade, the best choice for grade is 8%.

Overall pit economics may favour other grades due to geology, desired mineral extraction plans, or other factors, but this method of analysis enables comparison of alternate road designs. It is also important to recognise the inherent variability in the design parameters. Table 2-7 illustrates the common range in input design parameters. The road design is usually based on average or 'most likely' values. However, changing conditions can cause haulage productivity to drop significantly and operating and maintenance costs to increase. In some cases, it may be better to design the grade using probabilistic methods.

Table 2-7 Typical variability in road design parameters.

| Parameter | Field Range |
|---|---|
| Grade | ±5% |
| Rolling Resistance | 1% to 10+% |
| Empty Weight | ±5% |
| Payloads | ±20% |
| Horsepower | ±5% |

### 2.8.1 Maximum Sustained Grade

It is not be feasible to establish one optimum grade to suit all haul trucks. Furthermore, local conditions at a mine vary depending on the operator technique, season of the year, and daily road conditions. Therefore, the road designer must assess the braking and performance capabilities of the haulage fleet and, based on these data, determine whether available capital permits construction of ideal grades or steeper grades at the sacrifice of haulage-cycle time. The only guidelines for maximum grade that can be established with certainty are those established by the regulatory authorities in whose jurisdiction the haul road is located. In the United States, most States have established 15% as the maximum grade, while a few States allow grades up to 20%.

Length of sustained grades for haulage road segments is another factor that must be considered in vertical alignment. Many mine operators have found optimum operating conditions occur for maximum sustained grades no greater than 7% to 9%. Also, many state laws and regulations establish 10% as a permissible maximum sustained grade. However, this does not mean that vehicles cannot be safely operated on more severe grades.

Considering the foregoing factors, it is reasonable to accept 10% as maximum safe sustained grade limitation. For safety and draining reasons, long steep gradients should include 50m long sections with a maximum grade of 2% for about every 500 to 600m of steep gradient.

### 2.8.2 Runaway Provisions

Safety provisions to mitigate hazards caused by runaway trucks must be provided as part of the road design. One method is to use piles of loose granular material known as collision berms placed strategically along the centreline of the road. In case of brake or retarder failure, the truck operator manoeuvres the truck into the line with the pile so that the truck straddles the pile and is brought to a halt. Runaway or escape lanes are another method that can be used where space is available. Where zigzag haul roads are used, the escape lanes may often be conveniently located at the beginning of each sharp curve. The escape lane has a reverse grade (up to 20%) and is covered in a bed of loose gravel or coarse sand. Collision berms, while usually less expensive than escape lanes, can result in overturning of runaway vehicles.

## 2.9 Combination of Horizontal and Vertical Alignment

In the design of haul roads, horizontal and vertical alignments should complement each other. Potential problem situations to be avoided are:

- sharp horizontal curves at or near the top of a hill since the driver has difficulty perceiving the curve, especially at night or in foggy weather. If a horizontal curve is necessary, it should be started well in advance of the vertical curve,
- sharp horizontal curves hear the bottom hills or following a long sustained downgrades where haul trucks are normally at their highest speed,
- short tangents and varying grades, especially on multi-lane roads, and
- intersections near the crest of vertical curves or sharp horizontal curves. Intersections should be as flat as possible with sight distances being considered in all four quadrants.

The salient points to be considered when designing haul road alignments are:

- the operator should, at all times, be able to see ahead a distance at least equal to the vehicle stopping distance,
- sharp horizontal curves should be avoided at the top and at the bottom of ramps,
- intersections should be made as flat as possible and should not be constructed at the top of ramps,
- for a two-lane haul road, the minimum width should be 3.5 times the width of the largest truck in the haulage fleet. To safely negotiate sharp curves, this width should be increased by allowing for passing lanes and safety berms,
- for good drainage, road surface cross-slopes should be 1:25 and ditches should have “V” configurations with side slopes not exceeding 2H:1V,
- horizontal curves should be super-elevated by about 4% to 6% depending on the curve radius and equipment speed, and
- curve radius should exceed the minimum turning radius of the haulage equipment.

Depending on the contour of the original ground surface, the haul road may be constructed from cut sections, fill sections, and cut-and-fill sections. The relations between the type of section and stripping ratio and/or the amount of required fill should be analyzed to optimize the road location.

## 2.10 Safety Berms and Ditches

The road width (at sub-grade level) should also account for safety berm and ditches. Safety berms are typically constructed from mine spoil and are used to keep potential out-of-control vehicles on the road.

The height of the safety berm is generally about 2/3 of the diameter of tire of the largest vehicle travelling on the road. The slope of the sides of the safety berm can be as steep as 1H:1V, if the material stability permits. The safety berm is usually constructed with 1 to 2 m wide gaps spaced approximately every 25m to facilitate surface drainage off the road.

A drainage ditch is excavated on each side of the road. The ditch depth is variable but a typical value is 0.5m lower than the top of the sub-grade. The sides of the ditch should not be steeper than 3H:1V.

# 3 DESIGN OF HAUL ROAD CROSS-SECTION

## 3.1 Introduction

A haul road cross-section can be broadly divided into four layers as shown in Figure 3-1. The sub-grade is the naturally occurring surface on which the haul road is built. It may be levelled by excavation or back-filled in some cases to provide a suitable surface. Generally, suitable sub-base and base layer thicknesses are about 1 to 2m. However, sub-base thickness can be much larger (up to 10m) when a higher road elevation is required. Most mines use run of mine waste as road construction material for layers other than the surface layer. In some cases, the sub-base can be constructed from materials containing rocks larger than 100mm. Crushed rock with maximum particle size less than 100mm can be used for base layers. The surface layer is generally 0.3m to 1m thick.

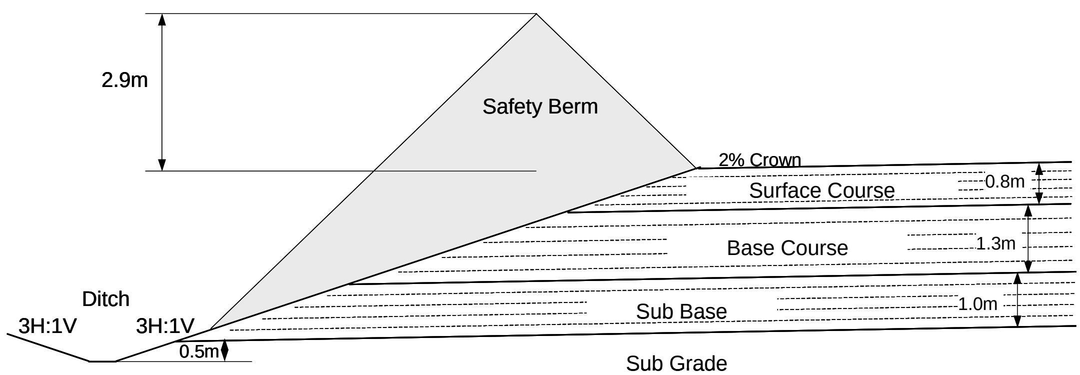


Figure 3-1 Typical haul road cross-section for 320t haul trucks.

In this section, structural aspects of haul road design will be discussed. A haul road cross-section can be divided into four distinct layers, namely sub-grade, sub-base, base and surface or wearing layers (Figure 3-1). The sub-grade is the existing ground surface on 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 embankment fill.

*Sub-grade:* The sub-grade can consist of native insitu soil or rock, previously placed landfill or mine spoil, muskeg, marsh or other existing surface over which a road is to be placed. 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 and muskeg will require substantial quantities of fill to help spread the heavy wheel loads and prevent rutting, sinking or overall road deterioration. Such adverse conditions, if allowed to occur, pose a serious threat to vehicular controllability and create unsafe haul road segments. If the sub-grade lacks the required bearing capacity, then it needs to be altered through suitable measures such as compaction or the use of geotextiles.

*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 effect of frost, accumulation of water in the road structure, and providing working platform for the construction equipment.

The sub-base distributes vehicle load 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. Obviously, topsoil is removed from the road route before the sub-base is installed. The soil has poor bearing characteristics and it is needed for restoration work along the finished road and embankments.

*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 high 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:* The uppermost layer of the haul road that comes directly in contact with tires is known as the surface 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.

Once the alignment of a haul road has been determined, the next design consideration is the actual construction of the road. The California Bearing Ratio (CBR) or a newer method based on a critical strain criterion and the construction material's resilient modulus can be used for haul road design. In both cases, an understanding of haul truck tire interactions is necessary.

Various methods exist for road design as summarized in Figure 3-2. These methods are used to calculate the appropriate thickness of each layer in the road by considering material properties such as plasticity index, California Bearing Ratio (CBR) or resilient modulus. The design method based on use of plasticity index has been limited mostly to the design of flexible pavement design for the commercial roads (Australian Asphalt Pavement Association 1983). A popular method of road design uses the CBR of the construction materials as a design criterion. This method originated in 1928-29 for design of commercial roads but found major application to construction of airfields after 1949.

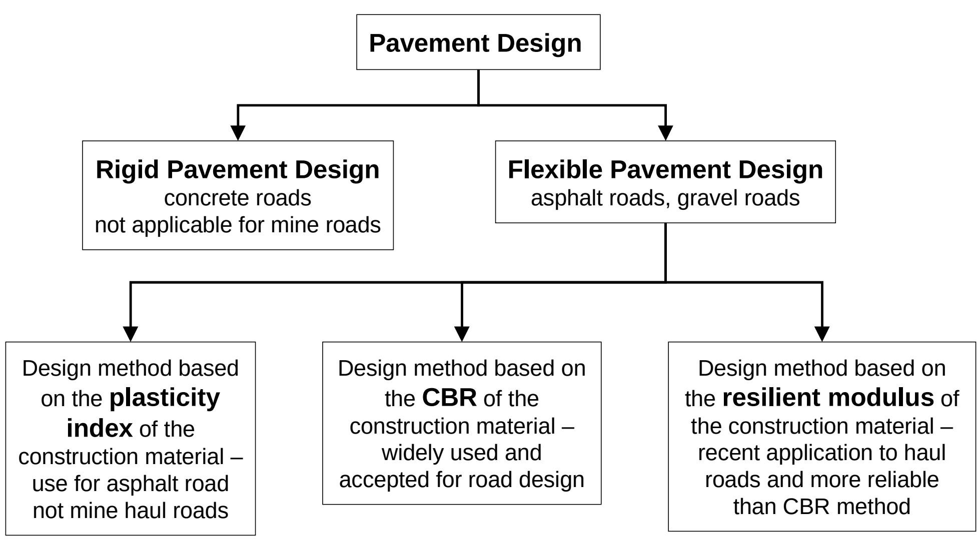


Figure 3-2 Types of pavement design.

Recent research on design of haul roads has highlighted a shift towards the use of a resilient modulus-based design method. In this case, the road cross-section is designed using predicted stresses and strains, and each layer's resilient modulus. A critical strain limit is used to establish the required moduli (and hence material and compaction properties) of each layer.

## 3.2 Design Based on CBR

One of the most widely used methods of computing required fill thickness for road construction is the California Bearing Ratio (CBR) method. This approach characterizes the bearing capacity of a given soil as a percentage of 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 first use of CBR (%) values to determine the cover thickness over the insitu material was reported by California Division of Highways during 1928-1929 (American Society of Civil Engineers 1950). This system was widely used in the 1940's and continues to be used by highway engineers for evaluating overall roadfill and interlayer thickness requirements for different sub-grade characteristics. Boyd and Foster (1949) addressed the dual wheel assembly problem through consideration of Equivalent Single Wheel Load (ESWL). Traffic volume and its effect on the structural design of pavements was considered by Ahlvin et al. (1971) in which a repetition factor was determined according to the load repetitions and the total number of wheels used to determine the ESWL. 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 CBR value, expressed as a percentage, is a measure of the resistance offered by a soil to the penetration of a cylindrical plunger, forced into the soil at a specified rate to a designated depth, to that resistance required to force the plunger into a standard crushed stone under the same conditions. The end area of the plunger is 1935mm$^2$ (3in$^2$), the specified penetration rate is 1mm/min (0.05in/min) and the depth of penetration is 2.5 - 5mm (0.1 - 0.2 inches). The test is conducted on the minus 20mm (minus ¾") fraction of a soil which is compacted by prescribed procedures into a 152mm (6") diameter mould. A 2.27kg (5lb) annular disk surcharge weight, which is intended to simulate the load of the pavement on the soil, is placed on the soil surface and the plunger is forced into the soil through the hole in the disk. The detailed procedure and apparatus used for conducting the test is described in the "Standard Test Method for Bearing Ratio of Laboratory-compacted Soils", ASTM Designation D1883.

The test may also be carried out on undisturbed soil samples taken in the field by the CBR mould, or on soaked or swelling samples. To minimize soil disturbance, the test can be conducted in the field on insitu deposits by jacking the plunger into the ground and measuring penetration by appropriately placed deformation gauges.

Design charts that relate pavement, base and sub-base thickness to vehicle wheel load and CBR values have been developed. A typical CBR chart is shown in Figure 3-3. Note that different empirical CBR design curves have been developed over the years for different applications. Some curves include a consideration of the number of loading cycles. The curves in Figure 3-3 depict cover thickness requirements for various wheel loads corresponding to a wide range of CBR values. The approximate bearing capacities for typical soils are included at the bottom of the graph for preliminary planning purposes only. For final design, CBR values obtained from testing the actual sub-grade and fill materials designated for road construction should be used in the CBR charts for determining fill thickness requirements.

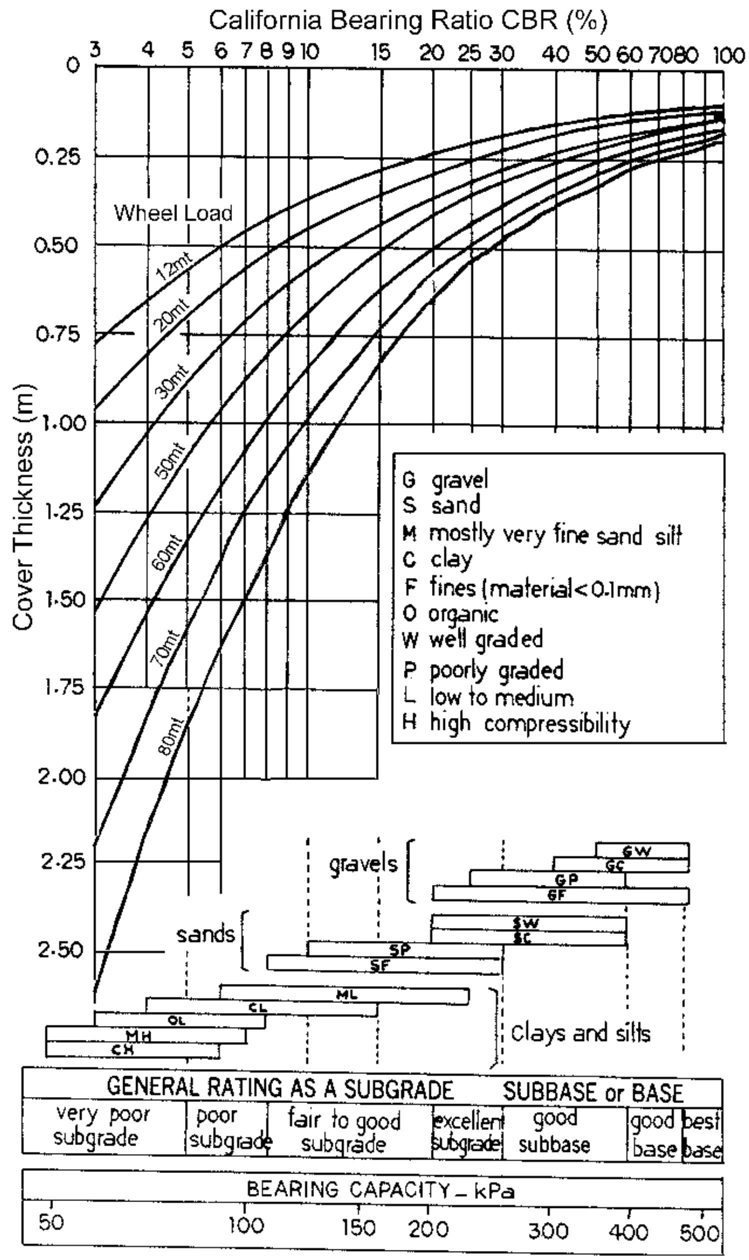


Figure 3-3 CBR curves (after Atkinson 1992).

Wheel loads for any haul truck can readily be computed from the manufacturer's specifications. Note that haul trucks are frequently loaded above their rated weight capacity and this 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 can be established. In every case, the highest wheel load should be used in the design computations. When a wheel is mounted on a tandem axle, the wheel load should be increased by 20% (Kaufman & Ault 1977).

Table 3-1 gives the calculated fill thickness using the CBR chart for a wheel load of 80mt (800kN). The required cover thickness for any material can be read from curves on Figure 3-3 corresponding to the CBR value of the material. For example, a sub-base material having CBR of 25 will require a cover thickness of 0.6m for an 80mt wheel load (Komatsu 930E). The layer thickness can be calculated by subtracting the cover thickness required by that layer from the cover thickness required by the layer that lies immediately below. The total required fill thickness in this example is 2.2m. Altering the assumed CBR for the sub-grade illustrates the sensitivity of the fill thickness to the underlying material properties.

Table 3-1 Haul road cross-section based on the CBR chart for a wheel load of 80mt.

| Layer | Typical material | CBR (%) | Total fill cover (m) | Layer thickness (m) |
|---|---|---|---|---|
| Surface | Crushed rock | 95 | - | 0.30 |
| Base | Pitrun sand & gravel | 60 | 0.30 | 0.30 |
| Sub-base | Till, mine spoil | 25 | 0.60 | 1.60 |
| Sub-grade | Firm clay | 4 | 2.20 | - |

Substantial reductions in CBR can result when fine-grained soils become saturated. Therefore, it is considered prudent to use the minimum CBR values when computing road fill thickness and accept the penalty of increased fill quantities as insurance against poor road performance should the fill or sub-grade materials become saturated by rising groundwater levels, inclement weather or spring run-off.

The CBR method is particularly useful for estimating the total cover thickness needed over the insitu subgrade material. A weaker subgrade requires thicker layers of road construction material. This moves the truck tires higher and away from the weak insitu material, thus diminishing the stresses or strains to a level that can be tolerated by the subgrade.

### 3.2.1 Modifications to CBR Design Method

The method discussed above can be improved upon by using equivalent single wheel load (ESWL) instead of single wheel load, as the road not only faces one wheel load but a combination of wheel loads thus increasing the stress level in various layers of the haul roads.

ESWL is calculated under the following conditions:

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

Foster and Ahlvin (1954) gave the following method for calculation of ESWL for various depths of a road cross-section. The deflection under a single wheel $D_s$ is given as:

$$D_s = r_s P_s F_s / E \qquad \text{Equation (7)}$$

Where: $r_s$ = contact radius for single tire (m)
$E$ = Young's modulus of the pavement (MPa)
$P_s$ = tire pressure for a single wheel (MPa)
$F_s$ = deflection factor for a single wheel

The deflection under a group of wheels $D_d$ is given as:

$$D_d = r_d P_d F_d / E \qquad \text{Equation (8)}$$

Where: $r_d$ = contact radius for a group of wheels (m)
$P_d$ = tire pressure for a group of wheels (MPa)
$F_d$ = deflection factor for a group of wheels

Following the assumptions for calculation of ESWL and the above equations:

$$D_s = D_d \text{ and } r_s = r_d \qquad \text{Equation (9)}$$

Tire loads ($L_s$ and $L_d$) are related to tire pressure and contact radius as follows:

$$L_s = \pi r_s^2 P_s \text{ and } L_d = \pi r_d^2 P_d \qquad \text{Equation (10)}$$

Therefore,

$$L_s / L_d = F_d / F_s \qquad \text{Equation (11)}$$

The above equation gives the relationship between tire load and the deflection factor. The deflection factors for various depth and horizontal locations are given in Figure 3-4, which can be utilized to calculate ESWL at various pavement depths for a given wheel geometry.

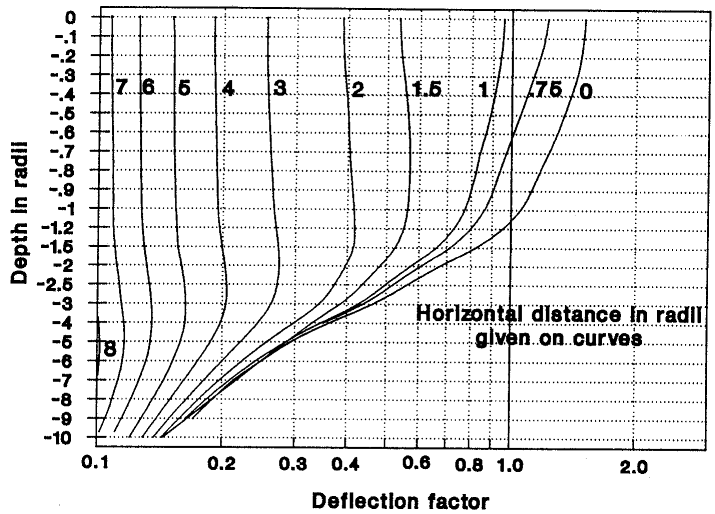


Figure 3-4 Deflection factor for ESWL determination with the distances normalized by radius of the tire contact area (after Foster & Ahlvin 1954).

Further details on calculation of equivalent wheel loads for mining haul trucks and their subsequent use as input into empirical CBR charts may be found in Shukla et al. (1989).

Yoder and Witczak (1975) reports four critical points for stress level under a truck as shown in Figure 3-5. The ESWL is calculated at a range of pavement depths from which the required cover thickness can be calculated using the CBR curve. The specific wheel grouping of a haul truck is reduced to four wheels by means of an equivalent single wheel load representing dual assemblies or axles and the deflections under four characteristic points are recorded. These characteristic points are derived from consideration of the stresses generated in a uniform homogenous pavement under the action of two sets of the two wheels, specifically the increase in stress (and thus deflection) where stress fields overlap.

The CBR method of haul road design has been very popular and has been used by many authors such as Kaufman and Ault (1977), Atkinson (1992) and Thompson (1996). The method is simple, well understood and can give fairly good design guidelines for most haul roads. The CBR design method has a number of inherent shortcomings that are discussed next. Nevertheless, this method serves as a rough check on designs developed using other methods.

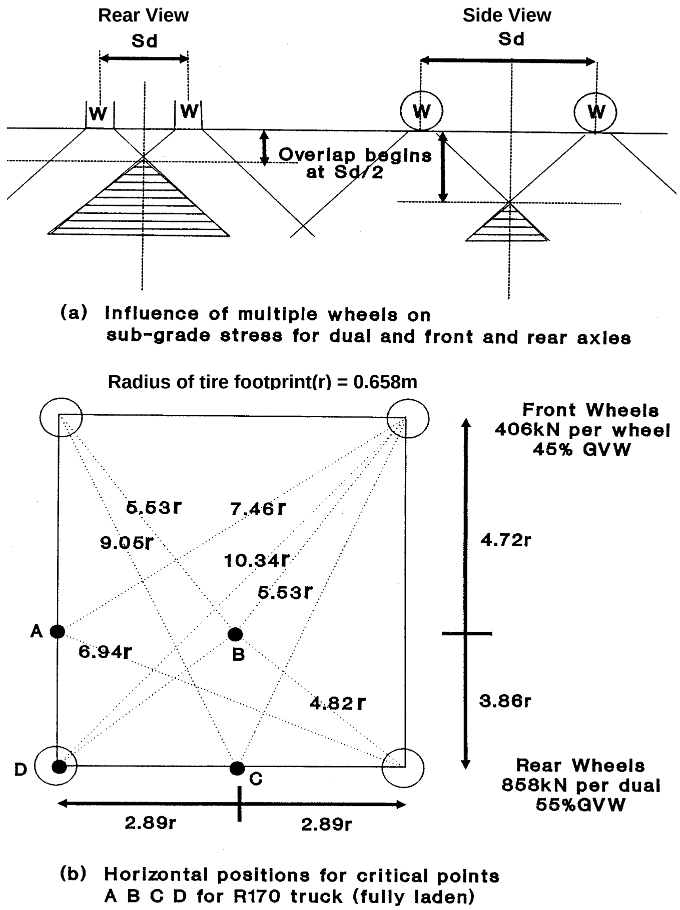


Figure 3-5 Critical points for a fully loaded truck (after Thompson 1996).

## 3.3 Design Based on Critical Strain and Resilient Modulus

Morgan et al. (1994) and Thompson and Visser (1997) criticized the CBR method of haul road design due to the following factors:

- The CBR method is based on the 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 and other properties.
- The CBR method does not take into account the properties of the surface 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 much different wheel geometry and construction materials.
- The empirical design curves were not developed for the high axle loads generated by large haul trucks and simple extrapolation of existing CBR design curves can lead to errors of under design, or even over design.

New road design methods take into account the differing properties in each layer and predict their behaviour before construction by appropriate laboratory and insitu testing. These methods enable road designers to use theoretical rather than empirical design approaches. The road cross section is treated as a composite beam. Morgan et al. (1994) and Thompson and Visser (1997) provide a haul road design method based on the strain caused in different layers of the haul road. Based on field observations, 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.

For a given stress in a layer, the induced strain is a function of the modulus of the material. The proponents of this design method (Morgan et al. 1994 and Thompson & Visser 1997) suggest the use of resilient modulus for describing the material properties of the layer. The resilient modulus is determined from a cyclic loading test. It is like a tangent Young’s modulus but it is measured after cyclic loading has compacted the test specimen. The cyclic loads lie below the peak strength. Because the specimen is compacted during the cyclic loading, the stiffness increases as seen in Figure 3-6. Hence, the nature of the test required to determine the resilient modulus is similar to the cyclic loading experienced in a road. AASHTO (1993b) T294 gives the laboratory test method to determine the resilient modulus of an unbound soil by repetitive loading of a soil sample in a triaxial chamber. It should be noted that this laboratory test is quite complicated and requires specialized test equipment.

Thompson (1996) estimated the resilient modulus by the falling weight deflectometer test. Alternatively, the Young's modulus of elasticity for a material can be determined by a compression test in laboratory. Figure 3-6 shows how the stiffness of a material increases with repetition of loading and thus the initial Young's modulus is lower than the resilient modulus. The test to measure the Young's modulus is simple and very well understood and may give a reasonable estimate of the resilient modulus, albeit on the conservative side as there is no confining pressure and stiffening of soil due to repeated loading. Mohammad et al. (1998) describes yet another method for calculation of resilient modulus using a cone penetration test with continuous measurement of tip resistance and sleeve friction.

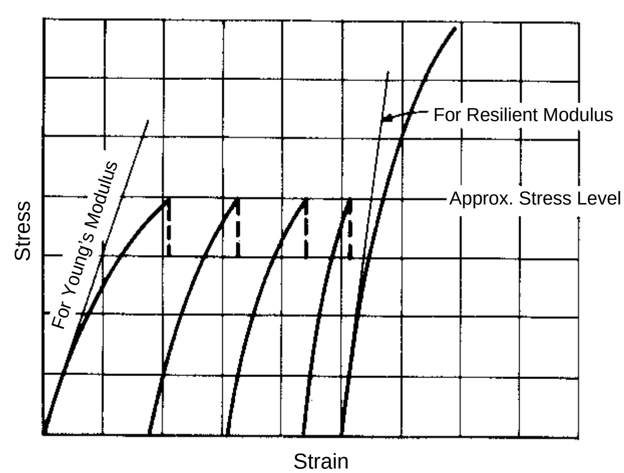


Figure 3-6 Method to obtain resilient modulus (after Bowles 1984).

The strains in a layer are a function of applied stress (tire pressure, size, and spacing) and the resilient modulus of the layer.

The wheel load of the haul truck can be obtained as described in the CBR method. The stresses in layers below the surface layer can be calculated using stress models or 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. Although the assumption of homogeneity of the haul road cross-section results in some error in estimation of the stress level in various layers, the assumption simplifies the problem for preliminary examination. The fore-mentioned assumptions combined with the theory of elasticity can be used to examine the stresses beneath a typical tire (Figure 3-7) with an inflation pressure, *p*. A typical haul truck tire has a foot print area of about $1.13m^2$ giving an equivalent diameter, *w* of 1.2m.

Figure 3-7 shows that the stresses in the base layer, which typically starts at 0.3 to 0.6m below the road surface, will be about 0.65 to 0.9 times the tire pressure or about 0.3 to 0.65MPa. Similarly, a typical sub-base begins at a depth of roughly 1.5m. Therefore, the sub-base experiences about 0.2 times the tire pressure or about 0.1 to 0.2MPa. Based on a strength criterion, appropriate construction materials for the base and sub-base need to have bearing capacities that exceed the expected stresses as shown in Table 3-2.

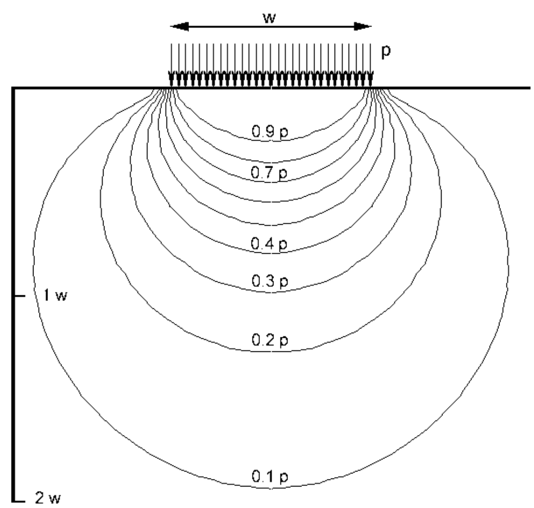


Figure 3-7 Stress bulbs below a circular pressure distribution.

Table 3-2 Minimum bearing capacity and Young's modulus of haul road construction materials.

| | Thickness (m) | Bearing capacity (MPa) | Young's modulus (MPa) |
|---|---|---|---|
| Surface | 0.3 to 0.6 | 0.7 to 0.9 | - |
| Base | 1.0 | 0.3 to 0.65 | 150 to 350 |
| Sub-base | 1.5 | 0.1 to 0.2 | 100 to 150 |

### 3.3.1 Critical Strain Limit

The important criterion for haul road design is a critical strain limit for each layer. A road cannot adequately support haul trucks when vertical strain exceeds a critical strain limit as the road ceases to act as a composite beam. Morgan et al. (1994) found that the critical strain limit was about 1500 micro-strain at the top of the sub-grade while Thompson and Visser (1997) noted that the limit was around 2000 micro-strains at the road surface. Somewhat different critical strain limits may be used for design depending on the design life of the road and traffic density. The strain limit depends on the anticipated number of haul trucks using the road over its working life. One empirical equation for estimating the critical strain limit is given by Knapton (1988). This equation was developed for heavy loading conditions found on docks at container ports. A modified version of the equation for haul roads shows that same functional relationship between the critical strain limit and the design life of the road and the traffic density:

$$E = 80{,}000 / N^{0.27} \qquad \text{Equation (12)}$$

Where: E = allowable strain limit (micro-strain)
N = number of load repetitions.

This equation has been developed for semi-permanent and permanent haul roads. A critical strain of 2000 micro-strain is obtained for about 800,000 load repetitions, which would be typical for a permanent haul road carrying 400,000 loaded trucks over its life span. If the number of load repetitions increases to 2.5 million, then the critical strain limit drops to about 1500 micro-strain. Semi-permanent or temporary roads will typically experience less than roughly 500,000 load cycles and hence a critical strain limit larger than 2000 micro-strain would be appropriate.

Using Equation 12, the critical strain limit for a permanent haul road can be calculated. Assume a haul road at a mine carries a yearly production of 22 million tonnes of ore and waste using haul trucks with a GVW of 375mt and average payload of 220mt. The mine has a 12-year operating life, but the road is only used for 5 years before experiencing planned maintenance and repairs.

Total load carried by the road in its life = 22,000,000mt/yr x 5yr = 110 million tonnes
Number of loaded trucks over life of road = 110,000,000/220 = 500,000
The number of load cycles (two axles) = 1,000,000 (ignore empty truck traffic)
From Equation 12, the critical strain limit =

$$E = 80{,}000 / (1{,}000{,}000)^{0.27} = 1919 \approx 1900 \text{ micro-strain}$$

Equation 12 seems to give reasonable critical strain limits for load repetition numbers ranging between 50,000 and 5,000,000. However, please note that Equation 12 needs further calibration for mine haul roads and may change in the future.

### 3.3.2 Design Procedure

Figure 3-8 presents a flow chart summary of the road design method based on the resilient moduli of the 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 the haul road, which gives the number of load repetitions during the design life of the road. Generally, this limit falls between 1500 and 2000 micro-strain.

Resilient modulus is the major input for modelling vertical strain. It can be determined either by a resilient modulus test (AASHTO 1993[b], T294) or by a falling weight deflectometer test. The Young's modulus gives a conservative estimate of the resilient modulus. The resilient modulus of a material is highly sensitive to compaction effort and water content during compaction. These factors must be considered when determining values for use in numerical models.

Once the critical strain limit has been established and the layer moduli at various depths below the tires measured or estimated, the next step is to determine the vertical stresses below the tire. Various methods can be used to calculate the stress distribution although numerical stress analysis programs are probably the easiest technique to use.

Initially, the thickness of each layer should be estimated based on past experience or designs at mines with similar conditions. For least vertical strain, the stiffest material should be put at the top, the next stiffest underneath it, and so on. For modelling strain, other material properties such as Poisson's ratio are also required. The increase in strain due to interaction of tires should also be considered. If the strain in any layer is more than the critical strain limit, then the thickness and/or the stiffness of the layer above that material should be increased. On the other hand, if the strain in any layer is much less than the critical strain limit, then the thickness of the layer above that layer can be decreased. The amount by which the thickness should be increased or decreased depends on the difference between the vertical strain and the critical strain limit. Initially, 0.1m is a good increment. In both cases the modelling should be repeated to ensure that the strain at all points is less than the critical strain limit.

The layer thickness determined by this method depends on the resilient (Young's) modulus of the haul road construction material. A low modulus construction material may result in a very thick layer, which may be unacceptable for economic or operational reasons. Then it becomes essential to investigate the use of improved compaction methods and/or the addition of cementing agents such as fly ash to improve the rigidity of the construction material and consequently to lower the fill height (volume) requirement. Strain modelling should be performed again to ensure that the vertical strain at all points is less than the critical strain limit.

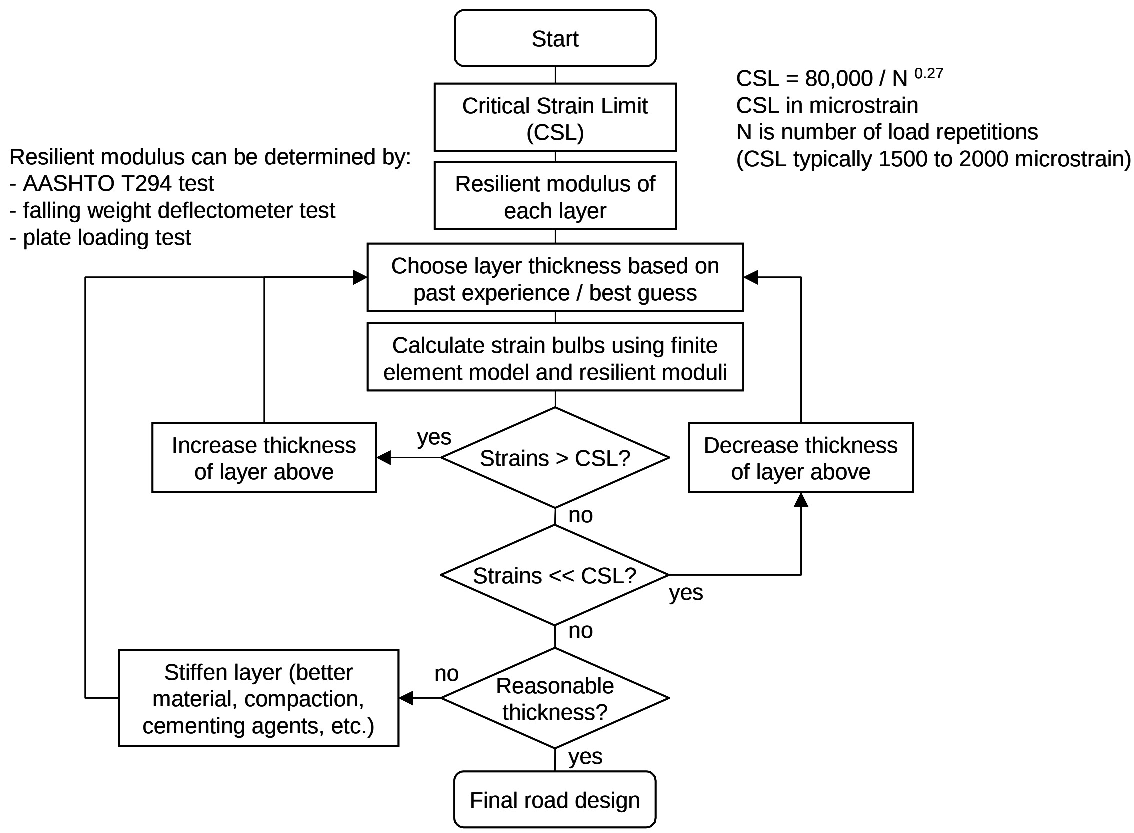


Figure 3-8 Major steps of the resilient modulus haul road design method.

## 3.4 Comparison of the Two Methods

As discussed in the previous sections, there are two different methods of haul road design. The first method is based on the CBR value of the construction materials, whereas the second method takes the resilient modulus and the unconfined compressive strength as the design criteria.

The CBR method estimates the bearing capacity of a construction material by measuring the resistance offered by it to a standard plunger whereas the second method relies on the measurement of the resilient modulus and the unconfined compressive strength (either insitu or in the laboratory) of the construction material.

The CBR method assumes that failure will occur when the cover thickness above a certain material is less than that required, according to a standard CBR chart. The failure criterion for the second method is based on the vertical strain in each layer of the haul road cross-section. It assumes that failure will occur when the strain at any point exceeds the critical strain limit. The critical strain limit is determined for a particular road depending on the number of loaded trucks expected to travel over it during the designed life of the road as discussed in section 3.3. The number of loads passing a particular section of a road depends on the designed life of the road as well as the traffic density. These factors, which are highly variable (e.g. designed life for a haul road can vary from few months to tens of years), are not directly taken into account in CBR method. Also, the CBR method does not take into account the bearing capacity of the surface layer, thus the selection of construction material for the surface becomes arbitrary in this method.

Moreover, failure by the CBR method is assumed to occur when the tire penetrates a haul road layer or an upper layer's material penetrates into the lower one, thus causing failure of the structure (as the method estimates the bearing capacity by measuring the resistance offered by a penetrating plunger) but failure can occur long before such condition arises. The haul road cross-section acts as a layered beam structure. Under excessive strain, this structure can cease to act as a beam, thus losing strength, and failure becomes imminent. Consequently, it can be expected that a design using CBR method would result in under-design in most cases. But in case of haul roads with very short designed life, CBR method can be over-conservative.

To illustrate the comparison, a hypothetical but realistic case of haul road design will be solved using both methods and the results will be analyzed.

Problem: Determine the thickness of various layers of a haul road for a given set of construction materials for an 80mt single wheel load (Komatsu 930E). The assumed material properties used for various layers are given in Table 3-3.

Table 3-3 Properties of the materials constituting different layers.

| Layer | CBR (%) | Compressive strength (kPa) | Resilient modulus (MPa) |
|---|---|---|---|
| Sub-grade | 3 | 80 | 40 |
| Sub-base | 10 | 150 | 80 |
| Base | 50 | 400 | 200 |
| Surface | 100 | 700 | 350 |

Critical strain limit = 2000 micro-strains
Tire diameter (*w* or 2a) = 1.2m
Type of pressure distribution = circular and uniform
Construction materials are homogenous, isotropic and elastic.

**CBR Method:** Using Figure 3-3 and the CBR values of the material given above, the cover thickness for each type of material was determined. The thickness of any layer is equal to the difference of the cover thickness required for that layer and that for the previous layer. Table 3-4 shows the layer thickness obtained by the method.

Table 3-4 Road layer thickness based on the CBR method.

| Layer | CBR (%) | Cover thickness (m) | Thickness of layer (m) |
|---|---|---|---|
| Sub-grade | 3 | 2.70 | - |
| Sub- base | 10 | 1.20 | 1.50 |
| Base | 50 | 0.45 | 0.75 |
| Surface | 100 | - | 0.45 |

**Method Based on the Critical Strain**:
Foot print area of the tire = $\pi\ (w/2)^2 = \pi\ (1.2/2)^2 = 1.13\text{m}^2$
Stress exerted by the tire ($q$) = load/area = 80*9.81/1.13 = 690kPa

The stress was estimated from Figure 3-7 using the tire width ($w$ or 2a) and the surface pressure ($q$). The thickness of various layers was selected such that the maximum stress level faced by any layer is less than the bearing capacity of that layer and the strain induced is less than 2000 micro-strains (or critical strain limit determined according to Equation 12, section 3.3.1).

This gives only a preliminary calculation of cover thickness. The result was checked with a stress-strain model, which considers variable resilient modulus of different layers. The thickness of the various layers was adjusted to bring strain at any point less than the critical strain limit. The results are shown in Table 3-5.

Table 3-5 Layer thickness based on the resilient modulus method.

| Layer | Bearing Capacity (kPa) | Resilient modulus (MPa) | Cover thickness (m) | Thickness of layer (m) |
|---|---|---|---|---|
| Sub-grade | 80 | 40 | 2.04 | - |
| Sub- base | 150 | 80 | 1.44 | 0.60 |
| Base | 400 | 200 | 0.58 | 0.86 |
| Surface | 700 | 350 | - | 0.58 |

The cover thickness required for the sub-grade obtained by CBR method is more than that obtained by the method based on the resilient modulus, but for other layers, the required cover thickness by CBR method is much less. So, the base and sub-base layers, if designed by the CBR method, may face excessive strain or structural failure. Thus, the CBR method results in under-design although the total cover thickness required by CBR method is greater than that required by the other method. This under-design will be more pronounced for a haul road with a longer design life as the strain limit would be lower than 2000 micro-strains, say 1500 micro-strains, thus increasing the thickness of the base and sub-base layers.

## 3.5 Correlation Between the Vertical Strain and Surface Deflection

While a critical strain criterion is useful for design purposes, it is useful to convert strains into displacements because displacements are easily observed in the field.

A number of haul road cross-sections were numerically analyzed to study the relation between vertical strain and the deflection generated both at the surface and the top of the sub-grade (Figure 3-9 & Figure 3-10). Following were the assumptions for the analyses:

- Tire pressure (uniform distribution over a circular contact area) and tire diameter are given in Table 3-7,

- Table 3-7 gives the thickness and modulus of various layers for different cases, and
- Poisson's ratio = 0.3 (for all materials).

Table 3-6 Truck sizes and tire pressure for various cases.

| | Case 1 | Case2 | Case 3 |
|---|---|---|---|
| Truck size (ton) | 170 | 240 | 320 |
| Tire pressure (kPa) | 550 | 690 | 690 |
| Tire contact diameter (m) | 0.94 | 1.01 | 1.26 |

Table 3-7 Modulus and fill thickness for various layers.

| Layer | Granular Fill Thickness (m) | | | Elasticity Modulus (MPa) |
|---|---|---|---|---|
| | Case 1 | Case 2 | Case 3 | |
| Surface | 0.3 | 0.6 | 0.8 | 331 |
| Base | 0.5 | 0.6 | 0.8 | 331 |
| Sub-Base | 1.0 | 1.0 | 1.0 | 83 |
| Sub-Grade | - | - | - | 41 |
| Total | 1.8 | 2.2 | 2.6 | - |

Numerical analyses involved determination of vertical deflection and strain at the surface and at the sub-grade induced in a given cross-section for a set four tire loads from the back axle of a truck.

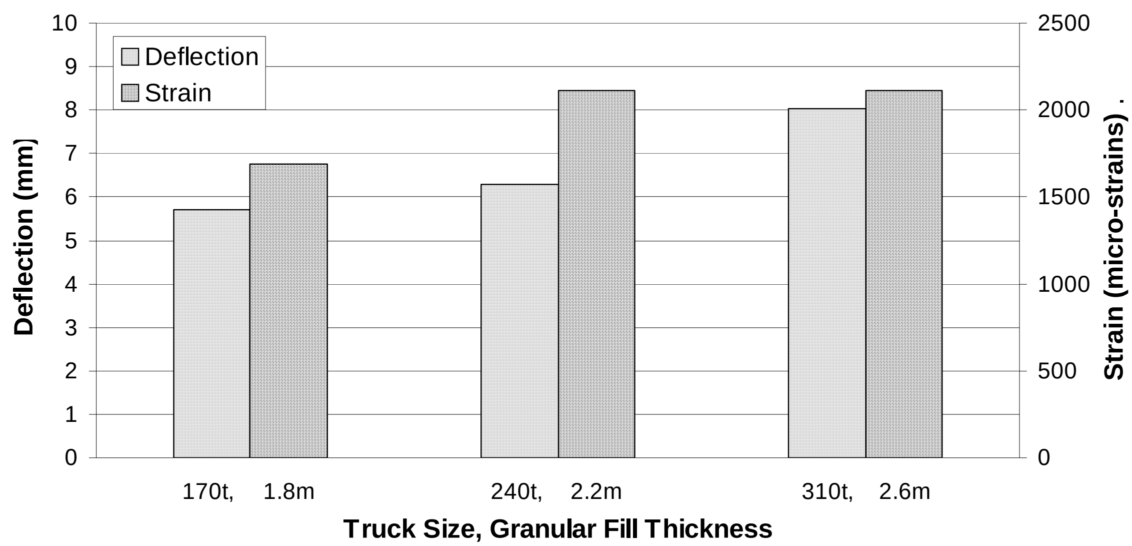


Figure 3-9 Deflection and strain at the surface of the haul road.


Figure 3-10 Deflection and strain at the top of the sub-grade.

Thus for 2000 micro-strain at the road surface and 1500 micro-strain at the top of the sub-grade, the corresponding deflection criteria computes to 6 to 8mm for the surface layer and 4 to 5mm for the sub-grade.

## 3.6 Summary

Many methods exist for road design. Of these the CBR and resilient modulus methods are particularly applicable to haul roads. Although the CBR method is a commonly accepted and applied method of haul road design in surface mines, it has many inherited shortcomings, which may lead to under or over design. For mines that use ultra-large trucks (GVW > 400mt), it becomes imperative to use a haul road design method based on the resilient modulus of the construction materials; this requires more complex analysis than the CBR method.

# 4 ROAD SURFACE

## 4.1 Introduction

Most mine haul roads are unpaved, therefore the selection, application and maintenance of the road surface or running surface is critical to trafficability. The condition of the 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 critical factors. Washboards, 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 and grow exponentially with the speed of the truck. Therefore, the road surface condition is especially important with today's much larger trucks operating at high speeds. Impact forces reduce tire life, increase tire costs, increase metal fatigue in the suspension and frame of trucks, increase maintenance costs and shorten truck life.

Because asphalt or concrete is expensive (and repairs are expensive), mine haul roads are usually surfaced with crushed gravel. A decision has to be made whether to use gravel taken/made from the mine's overburden or to purchase gravel from another source. Local gravel should be tested for durability and weathering resistance. It should not contain acid-generating materials (coal, refuse, etc.). When designing the surface layer of the road, the two major concerns will be tire adhesion to the road (traction) and the rolling resistance.

Traction is important from a safety aspect of keeping the haul truck from sliding off the road and rolling resistance is important from the aspect of truck speed and productivity. Another consideration is the “dusting” properties of the surface material. If the material is easily broken down by traffic or naturally has an abundance of loose fines then dust suppression will become a major road maintenance factor.

Usually maintenance of the haul road surface on a daily basis must be accepted as part of the overall design and cost. Generally, maintenance consists of watering, grading and compacting the road surface to maintain an appropriate profile.

## 4.2 Roughness

Road surface roughness is caused by the presence of potholes, washboards, swales, and bumps. These all have a detrimental impact on the life of truck components including the frame, suspension, power train, and tires. Impact forces transmitted through the truck components on a rough road are proportional to the GVW, but the magnitude of these impact forces is proportional to the square of the velocity at which the truck hits the rough spots. Driving over a rough road at high speed significantly reduces component life. Deslandes and Dickerson (1989) noted that surface roughness was the most significant factor influencing the structural fatigue life of haul truck frames.

Haul roads usually begin at a face and end at a dumping point. Field tests have shown that most of the shock loads on a truck frame typically occur within 150m of the face and dump. While it may be difficult to maintain good road conditions near the active face, effort should be devoted to careful design and maintenance of the road near the dump zone. In addition, careful matching of the bucket size to the truck size helps to minimize rock spillage.

Truck frames, like all steel structures, have a fatigue life. Fatigue is cumulative for steel structures, which means a truck frame remembers, or keeps a silent history of all the forces it has encountered. The highest 10% of impact forces do much more cumulative damage than the lowest 90%. Rough roads do more to reduce truck component life than any other single parameter. Rough roads also force the truck operator to reduce speed to safely navigate these hazards, hence production is reduced.

## 4.3 Traction

Road traction or friction coefficient between the road surface and the tire govern the potential for the vehicle to slide. Rolling resistance is defined as the combination of forces a vehicle must overcome to move on a specified surface. Generally, an increase in road surface traction is accompanied by a corresponding decrease in rolling resistance. Typical values of traction for various road surface materials are given in Table 4-1.

Table 4-1 Typical road traction coefficients for rubber tires.

| Road surface | | Traction coefficients |
|---|---|---|
| Concrete: | New | 0.80-1.00 |
| | Travelled | 0.60-0.80 |
| | Polished | 0.55-0.75 |
| | Wet | 0.45-0.80 |
| Asphalt: | New | 0.80-1.00 |
| | Travelled | 0.60-0.80 |
| | Polished | 0.55-0.75 |
| | Excess tar | 0.50-0.60 |
| | Wet | 0.30-0.80 |
| Gravel: | Packed & oiled | 0.55-0.85 |
| | Loose | 0.40-0.70 |
| | Wet | 0.40-0.80 |
| Rock: | Crushed | 0.55-0.75 |
| | Wet | 0.55-0.75 |
| Cinders: | Packed | 0.50-0.70 |
| | Wet | 0.65-0.75 |
| Earth: | Firm | 0.55 |
| | Loose | 0.45 |
| Clay Loam: | Dry | 0.55 |
| | Rutted | 0.40 |
| | Wet | 0.45 |
| Sand: | Dry | 0.20 |
| | Wet | 0.40 |
| Coal: | Stockpiled | 0.45 |
| Snow: | Packed | 0.20-0.55 |
| | Loose | 0.10-0.25 |
| | Wet | 0.30-0.60 |
| Ice: | Smooth | 0.10-0.25 |
| | Sleet | 0.10 |
| | Wet | 0.05-0.10 |

The addition of crushed material to the road surface during the winter or wet conditions to improve traction can pose a hazard to tires if the size and shape of the particles is too large. The use of finely crushed gravel of a uniform size is recommended.

Keeping roads clear of rock and debris is essential for achieving optimum tire life. Most mines have graders or rubber-tired dozers to clean up pits and roads. If this clean up is only performed once per shift, there is a lot of time for spillage to accumulate and tire damage to occur. If a machine cannot be scheduled for regular road maintenance, an operator should be available on call to clean a trouble section reported by a truck operator.

### 4.4 Rolling Resistance

Rutted and soft roads force the tire, hence the vehicle, to always travel uphill. An important measure of haul road surface conditions is the rolling resistance, i.e., the amount of drawbar pull or tractive effort required to overcome the retarding effect between the haul truck tires and the ground. In overcoming rolling resistance, the power of the vehicle is exerted to pull, in effect, the tire up and out of the rut, which is constantly created by the tire. Rolling resistance is usually expressed in terms of percent road grade or in terms of resistance force as a percentage of the GVW. For example, a truck travelling with 10% rolling resistance on a horizontal surface must overcome equivalent resistance to a truck travelling up a 10% grade with no rolling resistance. When viewed in terms of forces, a 10% rolling resistance is approximately equivalent to a required horizontal force of 10% of the truck's weight in order to move the truck forward.

Grade resistance is a measure of the force that must be overcome to move a truck over unfavourable grades (uphill). Grade assistance is a measure of the force that assists truck movement on favourable grades (downhill). Grades are generally measured in percent slope, which is the ratio between vertical rise or fall and the horizontal distance in which the rise or fall occurs. For example, a 1% grade is equivalent to a 1m rise or fall for every 100m of horizontal distance; a rise of 4m in 50m equals an 8% grade.

Uphill grades are normally referred to as adverse grades and downhill grades as favourable grades. Grade resistance is usually expressed as a positive (+) percentage and grade assistance is expressed as a negative (–) percentage. It has been found that for each 1% increment of adverse grade, an additional 10kg of resistance must be overcome for each tonne of truck weight. Therefore, grade resistance may also be calculated as a percentage of GVW using the relationship that grade resistance is approximately equal to 1% of GVW for 1% of grade.

Total resistance is the combined effect of rolling resistance (wheel vehicles) and grade resistance. It can be computed by summing the values of rolling resistance and grade resistance to give a resistance in kilogram force or an effective grade in percentage:

$$\text{Total Resistance} = \text{Rolling Resistance} + \text{Grade Resistance} \qquad \text{Equation (13)}$$

$$\text{Effective Grade (\%)} = \text{RR (\%)} + \text{GR (\%)}$$

An empirical expression for estimating rolling resistance is as follows (Caterpillar 1999):

$$\text{RR} = 2\% + 0.6\% \text{ per cm tire penetration} \qquad \text{Equation (14)}$$

Model tests, conducted by measuring the towing force required to move a relatively lightly loaded wheel over a sand or clay surface, suggest, however, that Equation 14 may significantly underestimate rolling resistance.

Effective grade is a useful concept when working with rimpull-speed-grade curves, retarder curves, brake performance curves, and travel time curves. Figure 4-1 shows that increased rolling resistance will slow a truck and increase fuel consumption.

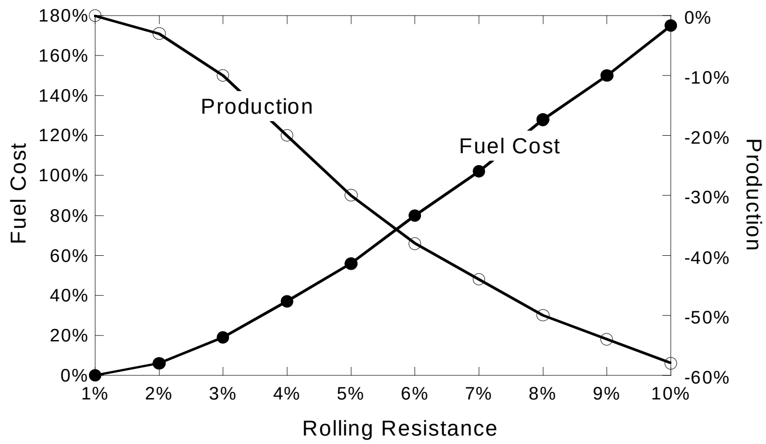


Figure 4-1 Rolling resistance versus performance.

Rolling resistance affects wear and tear on the truck, reduces fleet productivity, and increases operating costs such as fuel. Rolling resistance is composed of five main components:

- internal power train friction
- tire flexing under load
- tire penetration
- road deflection
- air resistance

The first two factors are approximately constant for a given haul truck but may vary with tire wear, type of tire and inflation pressure. Tire penetration, on the other hand, depends primarily on the wheel load, number of tires in contact with the ground (single, dual, or tandem) and the condition of the road surface.

For a given wheel load and tire configuration, more tire penetration or rutting will occur in weaker soils than in stronger, well-compacted soils forming the road surface. However, it is not necessary for tires to actually penetrate the surface for rolling resistance to increase. If the road flexes under load, the effect is nearly the same as the tire is always running “uphill”. Studies by Stuart and Peterson (1989) indicate that, especially for roads on oil sand formations, large elasto-plastic deformations occur not only beneath the wheel but well beyond the plan outline of the truck, a phenomenon that further contributes to rolling resistance.

Karafiath (1988) indicates that drive wheel slip is another factor that contributes to rolling resistance. Slip is especially significant when grade and rolling resistance are high or when the vehicle is being accelerated and wheel torque is 50% or more of the maximum torque. In off-road vehicle engineering, slip is defined as:

$$S = \frac{V_p - V_t}{V_t} \qquad \text{Equation (15)}$$

Where:
$S$ = slip (dimensionless factor)
$V_p$ = peripheral velocity of tire (km/hr)
$V_t$ = travel velocity of tire (km/hr)

The remaining factor that adds to rolling resistance is air resistance when the haul truck is in motion. Caterpillar assumes an increase in rolling resistance of 0.015% per km/hr, for vehicles travelling in the 0 to 65km/hr range. This corresponds to an increase of 1% x GVW in rolling resistance for a haul truck travelling at 65km/hr.

### 4.4.1 Measuring Rolling Resistance

Rolling resistance for a given road and haul truck type can be determined by pulling a loaded haul truck with another vehicle such as a grader or truck and measuring the pull force required to move the haul truck at a constant slow speed. The transmission of the loaded haul truck should be in neutral during the test. The test procedure is:

- weigh truck,
- locate suitable site with slight uphill grade to ensure continuous dynamometer gauge reading, record location and material description,
- assemble slings and dynamometer on the ground in the necessary location and position truck and tow vehicle (grader) such that dynamometer can be seen by the operator,
- connect slings to truck and tow vehicle,
- put truck transmission in neutral and signal the tow vehicle operator to slowly tension the slings and begin a slow even pull of truck,
- read dynamometer gauge upon attaining steady state motion, and
- determine grade (slope) of ground travelled during the test, using level, rod and chain.

Although determining rolling resistance by using equipment normally employed at the mine site provides reliable values, such procedures are expensive and tie up equipment. An alternative approach is to use a lightweight trailer to conduct the test and correlate the results with tests using mine haulage equipment. Being less expensive to operate, the lightweight trailer could be used to accumulate additional data more frequently and hence provide a monitoring role to indicate signs of road deterioration.

Kolada (1989) describes a specially constructed trailer that can be towed by a small truck to accurately measure rolling resistance using an on-board computer acquisition system. The sensors used to determine rolling resistance consist of a load cell, inclinometer and velocity sensor. The load cell, installed in the trailer drawbar, records the drawbar pull. Both tension and compression forces can be measured. The cell is protected from twisting action by a linear bearing assembly and from overloading by a protective casing. The casing also prevents contamination by dust and water. The grade of the road is measured by a pendulum-type inclinometer attached to the drawbar behind the load cell. Excessive pendulum oscillations, which occur on rough roads, are automatically smoothed out by a data averaging process. Accurate ground speed measurements, used to compute forces due to acceleration and deceleration, are made with a radar gun similar to those used by police.

The relevant expression for determining the rolling resistance force is:

**Error! Objects cannot be created from editing field codes.** Equation (16)

Where:

| | | |
|---|---|---|
| *F* | = | Force due to rolling resistance |
| *A* | = | Drawbar force |
| *B* | = | Extra force to travel uphill (negative if downhill) |
| *C* | = | Extra force required to accelerate (negative if decelerating) |

Supplementary sensors include triaxial accelerometers to measure road surface roughness and wheel magnets to provide an indication of wheel slip and traction on soft, slippery roads.

### 4.4.2 Typical Rolling Resistance Values

Typical rolling resistance values for different road surface materials from a test carried out at Highvale Mine are given in Table 4-2. At Syncrude Canada Ltd., rolling resistance tests were conducted on the native sub-grade prior to road construction and subsequently on the completed road after one year of service. The results are summarized in Table 4-3.

Table 4-2 Rolling resistance for various road surfaces at Highvale Mine (after Monenco 1983).

| Type of surface | Rolling resistance (%) |
|---|---|
| In-situ clay till | 4 - 6.7 |
| Compacted gravel | 2 - 2.7 |
| Compacted clay-gravel | 3.9 |
| Subsoil stockpile | 4.4 - 8.3 |
| Compacted clay till | 4.1 |
| Subsoil on mine spoil | 7.3 |

Table 4-3 Values of rolling resistance for Syncrude roads (after Van Wieren & Anderson 1990).

| Location | Winter (Good) | Summer (Average) | Spring / Fall (Poor) |
|---|---|---|---|
| Sub-Grade – oilsand | 4 – 6% | 6 – 9% | 9 – 12% |
| Sub-Grade – Clearwater | 4 – 6% | 6 – 8% | 8 – 10% |
| Sub-Grade – dump material | 7 – 9% | 10 – 12% | 12 – 16% |
| Road Surface – temporary | 3 – 5% | 4 – 6% | 4 – 6% |
| Road Surface – permanent | 3 – 5% | 3 – 5% | 3 – 5% |

Due to a shortage of conventional aggregate reserves for road construction at Syncrude Canada Ltd., supplementary materials were obtained from the following sources (Dionne 1987):

- crushed siltstone from overburden spoil
- sand and gravel in other areas of leases
- tailings sand
- washed/crushed extraction rejects
- off-site limestone quarries

To determine the bearing capacity and trafficability characteristics of the Clearwater Formation, Syncrude Canada Ltd. embarked on a test pit and field-testing program in 1983 prior to road construction. The Clearwater Formation, a layered marine deposit composed of varying amounts of clay, silt and sand, with clay being the predominate constituent, ranged in thickness from about

5m in the east mine area to a maximum of 25m in the west mine. The program consisted of excavating a 100,000bcm test pit utilizing a Demag H241 shovel and 170t Titan haul trucks. The excavated material was used for haul road construction tests and dump construction tests while the insitu materials were subjected to pressure cell tests, plate loading tests, California Bearing Ratio tests and haul truck rolling resistance tests. From the results of this program it was determined, among other things, that the Clearwater Formation could sustain a bearing pressure of up to 758kPa (110psi) without excessive rutting and that the H241 Demag shovel exerted a maximum track pressure of 738kPa (107psi) while digging. This demonstrated that large conventional shovels could be used in the Clearwater Formation provided the maximum bearing pressure was less than 758kPa (110psi) (Dionne 1987).

Table 4-4 and Table 4-5 list other values for rolling resistance. Various tire sizes and inflation pressures will affect the rolling resistance. The values in these tables are approximate, but can be used for estimating purposes when specific performance information on particular equipment and given soil conditions are not available.

Table 4-4 Rolling resistance for various types of road surface.

| Type of surface | Rolling resistance (%) | Reference |
|---|---|---|
| Cement, asphalt, soil cement | 2 | Kaufman & Ault (1977) |
| Hard-packed gravel, cinders, or crushed rock | 3 | Kaufman & Ault (1977) |
| Moderately packed gravel, cinders, or crushed rock | 5 | Kaufman & Ault (1977) |
| Unmaintained loose earth | 7.5 | Kaufman & Ault (1977) |
| Loose gravel and muddy rutted material | 10-20 | Kaufman & Ault (1977) |
| Asphalt | 0.8-1.5 | Johnson (1989) |
| Crushed limestone | 3.4-4.2 | Dionne (1987) |
| In-situ benonitic clay shale | 7-13 | Dionne (1987) |
| Loose snow | 4.5 | Caterpillar (1988) |
| Packed snow | 2.5 | Caterpillar (1988) |
| Concrete and asphalt | 1.5* | Euclid (undated) |
| Smooth, hard, dry dirt and gravel, well maintained | 2* | Euclid (undated) |
| Soft unplowed dirt, poorly maintained | 4* | Euclid (undated) |
| Wet, muddy surface on firm base | 4* | Euclid (undated) |
| Soft, plowed dirt or unpacked dirt fills | 8* | Euclid (undated) |
| Loose sand and gravel | 10* | Euclid (undated) |
| Deeply rutted or soft spongy base | 16* | Euclid (undated) |

* add 1.5% for every inch of tire penetration

Table 4-5 Rolling resistance factors (Caterpillar 1999).

| Underfooting | Rolling resistance, percent Tires Bias | Rolling resistance, percent Tires Radial |
|---|---|---|
| Very hard, smooth roadway, concrete, cold asphalt or dirt surface, no penetration or flexing | 1.5% | 1.2% |
| Hard, smooth, stabilized surfaced roadway without penetration under load, watered, maintained | 2.0% | 1.7% |
| Firm, smooth, rolling roadway with dirt or light surfacing, flexing slightly under load or undulating, maintained fairly regularly, watered | 3.0% | 2.5% |
| A dirt roadway, rutted or flexing under load, little maintenance, no water, 25mm tire penetration or flexing | 4.0% | 4.0% |
| A dirt roadway, rutted or flexing under load, little maintenance, no water, 50mm tire penetration or flexing | 5.0% | 5.0% |
| Rutted dirt roadway, soft under travel, no maintenance, no stabilization, 100mm tire penetration or flexing | 8.0% | 8.0% |
| Loose sand or gravel | 10.0% | 10.0% |
| Rutted dirt roadway, soft under travel, no maintenance, no stabilization, 200mm tire penetration and flexing | 14.0% | 14.0% |
| Very soft, muddy, rutted roadway, 300mm tire penetration, no flexing | 20.0% | 20.0% |

### 4.4.3 Economic Impact of Rolling Resistance

Rolling resistance can affect haulage costs in several ways. The most important cost involved with rolling resistance is the cost of fuel. Moreover, the rolling resistance and the smoothness of the haul road also affect tire life and wear, and fatigue of haul truck components.

Total resistance (grade plus rolling) offered by the haul road greatly influences the fuel consumption by the truck. For example, a mechanical drive truck (e.g. CAT 793) has to shift to a lower gear to negotiate higher resistance (Figure 8-3 & Figure 8-4). For analyzing the effect of rolling resistance only, start by assuming grade resistance equal to zero (flat surface). For a rolling resistance of 6% (fairly good haul road surface), the truck (CAT 793C, Figure 8-3 & Figure 8-4) can travel in 5$^{th}$ gear at 35km/hr. If the haul road is not well maintained then the rolling resistance may increase to a value of 15% or higher. Consequently, the truck has to shift down to 4$^{th}$ gear or lower and the speed of the truck drops down to 20km/hr or lower. Thus, the truck will consume significantly more fuel to traverse the same distance. Similarly, for electrical drive trucks, the RPM of the engine increases with the increase in the resistance.

The cost due to loss of productive time of the truck (as the truck takes longer to traverse the same distance) and the cost of additional maintenance (due to higher wear/ tonne of material moved) must also be considered.

Another major impact of the rolling resistance on haulage cost is through the tire costs. Tire life (thus the cost) is very sensitive to the rolling resistance and the overall quality of the haul road. Table 4-6 shows approximate reduction in tire life due to various haul road conditions. Poor maintenance of haul road may lead to 20% or more reduction in tire life, thus increasing the tire cost.

Table 4-6 Reduction factors for tire life (Barton 2000).

| On site conditions | Reduction factor |
|---|---|
| Average soil – no rock | 0% |
| Average soil – scattered rock | - 10% |
| Well maintained road with smooth gravel | - 10% |
| Poorly maintained road with ungraded gravel | - 30% (or more) |
| Scattered blast rock | - 40% (or more) |

Rolling resistance and overall smoothness of road also affect the general wear and fatigue of the various parts of the truck, thus influencing equipment life as well as the maintenance cost. Thus, maintenance of haul road improves the economics of the haulage system and increases the productivity (and production capacity) of the same haul truck /road combination.

## 4.5 Haul Road Trafficability and Cycle Time

Wait time, delays and operator efficiency all impact cycle time. Minimizing truck exchange time can have a significant effect on productivity. Total cycle time is the combination of fixed time and travel time. Fixed time for haul trucks includes: truck loading time (varies with loading tool), truck manoeuvre in load area (truck exchange, typically 0.6-0.8 min.), and manoeuvre and dump time at dump point (typically 1.0-1.2 min.). The travel time includes hauling time (loaded) and return time (empty) (Figure 4-2). The travel time can be adversely affected by the haul road's surface condition.

Given a 1.6km one-way haul distance on flat ground, and 1.8 minutes combined loading and dumping time, the impact of a change in rolling resistance from 4% (good road) to 10% (moderately poor road) can be seen from Figure 4-2. At a 4% effective grade, the travel times for a loaded and unloaded CAT 793C truck are 2.9 and 1.8 minutes respectively or a combined time of 4.7 minutes. If the same road has a surface that deteriorates such that the effective grade becomes 10%, the combined travel times nearly double to 9.5 minutes. The total cycle time increases from 6.5 minutes to 11.3 minutes, which has a substantial negative effect on productivity and haulage costs.

The area that usually causes most damage to the tire and truck is not on the haul road itself, but the loading and dumping areas. Restricted space often results in tight turns and steep grades. At the loading area, the road is usually short lived and rarely engineered or constructed anywhere near to the standards of a permanent haul road. The high levels of traffic and the loading operation often produce a greater amount of loose rock on the rock. These combinations lead to tire wear and damage. Special effort is needed to keep the loading area clear of loose rocks. The dump area should also be kept clean. In addition, it is important to build an adequate turning area for trucks entering a dump to minimize stress on the tire sidewalls.

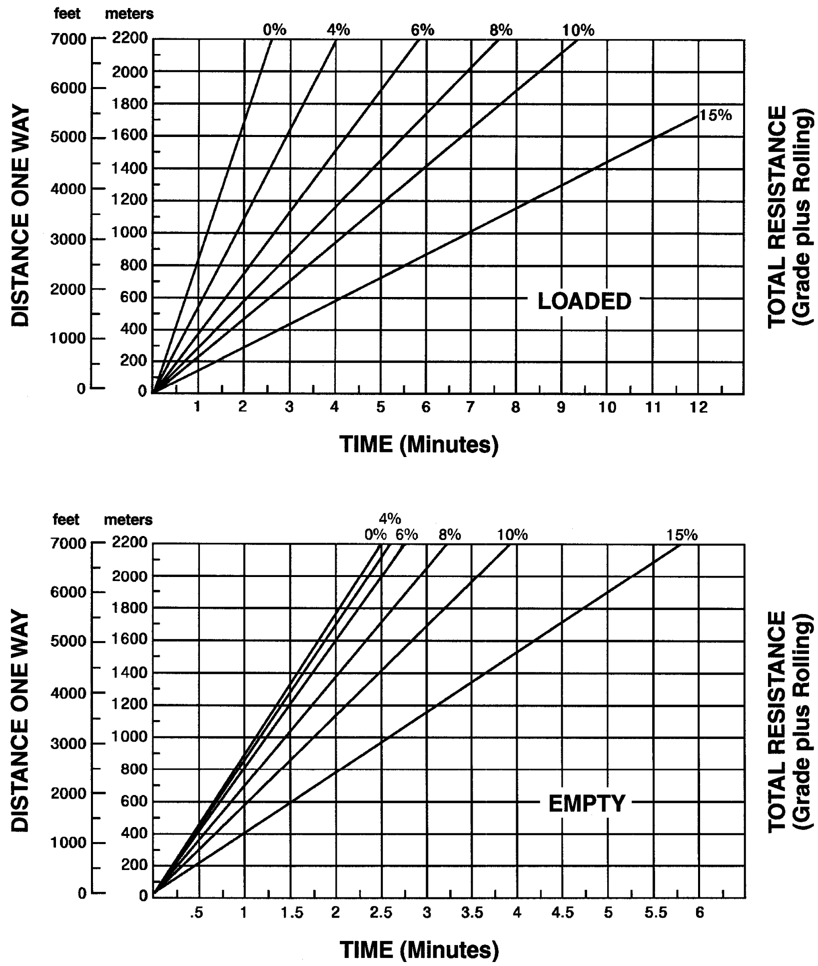


Figure 4-2 CAT 793C travel time on 40.00R57 tires (Caterpillar 1999).

One or more of the following conditions primarily cause poor haul road trafficability and high vehicle rolling resistance:

- high groundwater levels within the road fill,
- excessive fines in the surface and base layer coupled with high moisture contents due to inadequate road crown and/or ditches,
- uniform rather than well-graded material placed in the surface and base layers,
- insufficient depth or incompatible grading of road fill placed on soft, wet sub-grade soils,
- bentonitic soils used in the surface layer,
- insufficient fines to act as a binder in the surface layer, and
- rock and debris left on the road surface.

## 4.6 Road Maintenance and Repair

Lack of road maintenance can increase the operating cost for haulage. For example, observations at a metal mine showed that nearly three quarters of all tire failures were caused by cuts and impacts. These failure modes can be managed with proper road construction and maintenance. If only one 37.00R57 tire fails prematurely, say at half its normal life, the cost is the same as about 150 hours of operation of a 16G motor grader. The grader is an important haul road management tool. Proper maintenance of the road surface minimizes the effect of bumps, holes, spillage, and rolling resistance on the haulage fleet.

Haul roads should not be allowed to remain rutted or grooved. Running a tire on a rutted road can cut the sidewall and put stress on the carcass when the truck enters and leaves the rut. Plus, once in the rut, a tire will wear unevenly because the surface is generally not flat.

Graders are used to keep the road surface smooth to maintain cross slope, and to remove loose rocks from the surface. Graders are also used to remove snow, keep ditches clean, and build the road.

All roads deteriorate gradually with time due to the effect of weather and repetitive loading from passing vehicles. Road maintenance can slow the rate of deterioration, but eventually a point is reached where repairs or rehabilitation is necessary. For permanent roads, the repair may involve removal of the surface layer and replacement and compaction of portions of the damaged base and sub-base. Often the existing surface layer can be scarified and recompacted followed by placement of an additional thickness of compacted gravel on top. Rehabilitation of the road may be a strategy used to extend the life of a road.

## 4.7 Drainage Requirements

Poor drainage from the road surface leads to mud and potholes resulting in tire spinning, fast wear, cuts, reduced traction, and increased fuel consumption. Structural damage to the road itself can occur if water is allowed to penetrate into the various road layers. Safety berms along the sides of the road require appropriately spaced gaps to create outlets for surface water.

A wet running surface contributes to cuts in tire treads and sidewalls. The water acts as a lubricant for rubber and wet rubber cuts more easily than dry rubber. Therefore, do not over-water haul roads for dust suppression. Standing water on the road surface conceals tire hazards such as sharp rocks or ruts.

The road surface should have a crown of 2 to 4% to promote rapid drainage of surface water. Steeper crowns are preferred from a surface drainage perspective but they can increase tire wear and metal fatigue in the truck.

High groundwater levels in the sub-grade and road fill give rise to diminished bearing capacity, excessive rutting, high rolling resistance and, in high embankments, instability of road side slopes. Excess water retained within the road can be forced upward by the 'pumping action' of passing vehicles. This can eventually degrade the bearing capacity of the road as the fill layers loosen (both material stiffness and strength drop). Seasonally fluctuating water levels can also result in uneven settlement of the road surface.

In areas of naturally occurring high water table such as swamps or areas containing muskeg or watercourses, good drainage must be used to maintain low water levels in the road fill. This is usually accomplished by providing and maintaining adequate ditches along the road alignment, lateral ditches for swamp or muskeg drainage, culverts over streams and/or placing a sufficient depth of fill over the poor ground to ensure the stress increase due to traffic wheel loads is minimal at sub-grade level.

From a reclamation point of view, no road may contribute additional silt or erosion. Therefore, all roads need to be ditched, each with regularly spaced silt traps, and the ditches need to be maintained. A rock lining is needed in steep ditches (>8%) to prevent erosion. Ditches must lead to diversions and the water from the diversions led safely to settling ponds. Temporary silt traps in the ditches and diversions can be made from bails of hay, staked into the path of the ditch. Haul roads should have a crown that causes water to run to the side and then to the ditch. Permanent silt traps usually consist of an excavated pit and these require maintenance. Hillside roads have the ditches placed on the up-hill side of the road to ensure that they will not be washed out.

Culverts are typically used where roads cross streams or natural drainage paths. The culverts should be buried deep enough to prevent being crushed by vehicles passing over them. Unless the culverts lead to additional diversionary ditching, they need special water run-outs to reduce the velocity to the point where the water is non-erosive. On shallow slopes (less than 10%) with limited water flows (<0.5m/s), this may be done with vegetated outflow areas. Energy dissipaters (riprap or dumped-rock) may be required where flow rates are high.

Where permitted by local regulatory authorities, rock-fill causeways are sometimes used at watercourse crossings in lieu of culverts. In such cases, coarse rock up to 1m in diameter is end-dumped from the advancing causeway, allowing the coarser fraction to accumulate at the base of the fill by segregation.

Haul roads constructed along mountain slopes may interrupt surface run-off channels or block natural springs emerging from the mountainside. To prevent high groundwater levels within the road embankment, free draining rockfill, clean sand and gravel or a culvert should be installed at the base of the fill. High water levels occurring in existing road fills can often be lowered by installing, at appropriate spacing along the downstream slope, perforated horizontal drain pipe or backhoe-excavated finger drains that are backfilled with gravel.

Trafficability on temporary in pit roads with high ground water levels can be improved by placing a gravel or rockfill pad over the offending area or by installing pumping wells to lower the water table. The latter procedure may be cost effective if it also reduces the water level in, and improves the stability of, the shovel working face.

## 4.8 Dust Suppressants

Dust generated by moving vehicles can reduce visibility to dangerous levels and harm engines. Dust is typically reduced by application of water to the road surface. In the dry season, watering helps maintain compaction and strength of the surface layer. It also maintains the surface shape and reduces the loss of gravel. Watering also helps reduce wash boarding or corrugation of the haul road surface. The generation of a corrugated running surface is a dry weather phenomenon.

The quantity of water needed to control dust depends on the nature of the road surface, traffic intensity, humidity and precipitation. During the summer months, a typical road may require 1 to 2 litres per square metre per hour.

Liquid stabilizers and polymers can also be used. In addition to dust suppression, these can help strengthen the surface layer as well as provide a degree of water proofing.

Field trials to evaluate the effectiveness of various dust suppressants were conducted over a two-month period in the summer of 1986 on a segment of haul road of Highvale Mine (Monenco 1986). The site consisted of seven 300m long by 25m wide contiguous sections which included two untreated control sections, one water test section and a single section for each of the following dust control chemicals – emulsified asphalt, calcium chloride, calcium lignosulfonate and a surfactant. The chemicals were applied to the road surface using rates and procedures recommended by the supplier and literature sources. In the water test section, water was applied through a sprinkler bar attached to the mine water truck generally used for the purpose.

The characteristics of the chemical products used are as follows:

- Emulsified Asphalt – contains an emulsifying agent, water and asphalt, and cures by evaporation of water from the mixture. A product called DL-10 asphalt emulsion was used for this application. DL-10 is designed to remain flexible after curing allowing for road maintenance without loss of dust control effectiveness.
- Calcium Chloride – a hygroscopic compound that extracts moisture from the atmosphere and dampens the road surface. The product used for this program was natural salt brine with a minimum calcium chloride content of 26%.
- Calcium Lignosulfonate – an organic by product of the sulphite wood-pulping process that can be used to physically bind soil particle together.
- Surfactant – substance capable of reducing the surface tension of the transport liquid, thereby allowing available moisture to wet more dirt particles per unit volume. Alchem Inc. supplied a surfactant called Alchem 8808 for this application.

The procedures used for applying the various palliatives are summarized below:

DL-10 Asphalt Emulsion – (one application)

- The road surface was scarified to a depth of approximately 50mm using the shanks on a road grader,
- The scarified material was placed in windrows on the haul road shoulder,
- About one-half of the emulsion was applied, and
- The windrows were graded over the road surface and the remainder of emulsion was applied.

Calcium Chloride – (two applications ten days apart)

First Application:

- The upper 13mm to 25mm of the road surface was graded off and placed in windrows on the road shoulder,
- One-half of the calcium chloride solution applied, and
- The windrows were bladed over the road surface before applying the remainder of the calcium chloride solution.

Second Application:

- The road surface was scarified to a depth of 150mm and the loose material was placed in five windrows evenly spaced across the roadway,
- Approximately one-half of the solution was applied between the windrows, and
- The windrows were levelled and the balance of the solution was applied.

Calcium Lignosulfonate – (one application)

The calcium lignosulfonate was applied using the procedures noted above for the initial calcium chloride application. The material was applied at a rate of 1.5 litres of concentrated lignosulfonate per square meter. The concentrate was cut 50/50 with water so that the dilute solution was applied at a rate of 3.0L/m$^2$.

Surfactant – (nine applications 2 to 4 days apart)

The surfactant (Alchem 8808) was unlike the other chemical palliatives in that no special road preparation was required. The material was supplied in 22L pails that were manually emptied into the inlet at the top of the water truck as the tank was filled with water. The first five applications were at a surfactant concentration of 2% of the applied water volume whereas subsequent applications were at a concentration of 1%.

The emulsified asphalt, calcium chloride and calcium lignosulfonate solutions were applied using tanker trucks equipped with solution pumps and rear spray bars. Water trucks normally used for haul road dust control applied the surfactant solution. At the time of the initial chemical applications in mid-June, the haul road was in good condition with a well-compacted surface generally free of ruts, depression and potholes. The quantity of the different suppressants applied during each application and the approximate cost per kilometre are summarized in Table 4-7.

Table 4-7 Application rate and cost of dust control (Monenco 1989).

| Chemical | Unit cost* ($/L) | Application rate (L/m2) | Cost per km per application** (1986$) |
|---|---|---|---|
| Asphalt emulsion | 0.26 | 1.8 | 11,700 |
| Calcium chloride | 0.11 | 2.2 | 6,000 |
| Calcium lignosulfonate | 0.30 | 1.5 | 11,300 |
| Surfactant | 2.95 | 0.009 | 650 |
| Water | ----- | ----- | 35 |

* supplied and applied

** for 25m wide road surface

Effectiveness of the various dust suppressants was monitored in two ways:

- visual evaluation and assignment of a rating between 0 (worst condition) and 5 (best condition), and
- total and fixed dustfall analyses of samples collected from two dustfall stations located at the midpoint of each test section.

Total dustfall is defined as the amount of material left after evaporation of a dustfall sample and its subsequent drying. It includes both suspended and dissolved materials. Fixed dustfall is the residue that is left after ignition of the total dustfall sample.

A review of the test results showed that calcium chloride was the most cost-effective control chemical evaluated during the study program. It had the lowest single application cost and was as effective and long lasting as any other chemical. The sensitivity of the results was such that accurate, quantitative estimates of calcium chloride's effectiveness were difficult to develop. A judgmental review of the data suggested that a single application of calcium chloride would provide an average control effectiveness (i.e. % of uncontrolled dust emissions eliminated by the dust palliative) of about 25% over a period of approximately three weeks.

It was considered that water application once every two hours would provide a level of control effectiveness similar to calcium chloride applied once every three weeks. A single water application provides a measure of dust control for approximately one hour after the truck has passed. Cost for each dust control technique was estimated to be in order of $60,000/km for a six-month (April to September) dust control season. All of these estimates are for road sections that are in constant use throughout the control season. Cost would be proportionately lower for sections used intermittently.

# 5 ROAD CONSTRUCTION MATERIALS

Selection of appropriate materials is very important for road construction. The selection is based on material properties such as grain size distribution, compressive strength, weathering characteristics and rigidity. The material may have to be crushed to meet a particular particle size distribution. The surface or running layer requires the best available material, because it faces the greatest weathering and highest dynamic loads due to truck travel.

## 5.1 Surface Layer Materials

Surface layer design is slightly different from that of the other layers because apart from meeting the general requirements as for the other layers, the design should take care of operational requirements such as dust control, smoothness of ride, traction and rolling resistance. Material selection is usually based on local experience or guidelines related to unpaved public road construction. However, the unique service condition experienced by mine haul roads requires development of specifications tailored to those particular needs (Thompson and Visser 2000).

Compacted natural gravel and crush rock and gravel mixtures are widely used in surface mines for road construction, especially for the base and wearing layers. These materials can yield low rolling resistance and high traction, and can be constructed and maintained at a relatively low cost.

When considering surface material for construction of haul roads, the following types of material can be used:

- compacted gravel
- crushed stone
- ashphaltic concrete
- roller compacted concrete (RCC)
- stabilized earth

After visiting over 300 mining operations in the United States, Kaufman and Ault (1977) provided the following pertinent comments on haul road surface materials. At many mine sites, especially small coal mining and quarry operations, little consideration appeared to be given to the construction of a good haulage road surface. In fact, development of the haulage way is frequently accomplished by simply clearing a path over existing terrain. While this practice is undoubtedly the most economical means of road construction in terms of initial cost, the benefit is seldom long-lived. Failure to re-establish a good haulage road surface will result in increased vehicle and road maintenance costs, and will severely retard the ability of a vehicle to safely negotiate the route. These difficulties are usually greatest on earth and bedded rock surfaces. Greater vehicle maintenance is required on rock surfaces because of excessive tire wear. It is virtually impossible to construct a bedded rock surface free of jagged edges. Thus, scuffing continually cuts the tires of traversing vehicles.

Earth roads, unless thoroughly compacted and stabilized, may cause both vehicular and road maintenance difficulties. Dust problems are frequent during dry seasons and, if not controlled, the dust can contaminate air filtration components, brakes, and other moving parts, making frequent replacement of these items necessary. Moreover, dust represents a major safety hazard to the vehicle operator in that it can become so dense that visibility is severely reduced. Eliminating the dust problem requires continual wetting of the surface, which represents yet another maintenance expenditure. When subjected to heavy wetting, non-stabilized earthen roads become extremely slick and severely defaced by erosion, and maintenance must be increased to eliminate erosion gullies. Water also lubricates edges of rock fragments and allows them to penetrate tires easier. Jagged rock and unconsolidated earth surfaces should always be avoided in a safe haul road design.

The most practical construction materials for developing a haulage road surface that will ensure maximum safety and operational efficiency are crushed stone or gravel, asphaltic concrete, relocate and stabilized earth. The advantages and disadvantages of each material are discussed in the following paragraphs and summarized on Table 5-1.

Table 5-1 Advantages and disadvantages of various road surface materials (Monenco 1989).

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

### 5.1.1 Compacted Gravel and Crushed Rock

Generally the surface layer is constructed using high quality gravel crushed to –19mm size (Young's modulus about 330MPa, Cameron & Lewko 1996). Thompson (1996) reports use of a 200mm thick layer of material having resilient modulus in the range of 150-200MPa compacted to 98% modified AASHTO for a 170mt haul truck. For larger trucks, thicker layers with material having higher modulus of elasticity should be used for the surface layer.

The American Association of State Highway and Transportation Officials (AASHTO): M147 (1993[a]) gives the following guidelines for surface layer aggregates for public unpaved roads:

- Coarse aggregate retained on the 2.0mm (No. 10) sieve shall consist of hard, durable particles or fragments of stone, gravel or slag. Materials that break up when alternately frozen and thawed or wetted and dried shall not be used.

- Coarse aggregate shall have a percentage of wear, by the Los Angeles Abrasion test, AASHTO T96, of not more than 50.
- Fine aggregate passing the 2.0mm (No. 10) sieve shall consist of natural or crushed sand, and fine mineral particles passing the 0.075mm (No. 200) sieve.
- The fraction passing the 0.075mm sieve shall not be greater than two-thirds of the fraction passing the 0.425mm (No. 40) sieve. The fraction passing the 0.425mm sieve shall have a liquid limit not greater that 25 and a plasticity index not greater than 6.
- All the materials should be free from vegetable matter and lumps or balls of clay. The soil-aggregate material shall confirm to the grading requirements of Table 5-2.

Table 5-2 Grading requirements for soil-aggregate materials for surface layer (after AASHTO 1993[a]).

| Sieve designation | | Mass percent passing | | | |
|---|---|---|---|---|---|
| Standard (mm) | Alternate | Grading C | Grading D | Grading E | Grading F |
| 25.0 | 1 in. | 100 | 100 | 100 | 100 |
| 9.5 | 3/8 in. | 50-85 | 60-100 | - | - |
| 4.75 | No. 4 | 35-65 | 50-85 | 55-100 | 70-100 |
| 2.00 | No. 10 | 25-50 | 40-70 | 40-100 | 55-100 |
| 0.425 | No. 40 | 15-30 | 25-45 | 20-50 | 30-70 |
| 0.075 | No. 200 | 5-15 | 5-20 | 6-20 | 8-25 |

Because gravel or crushed rock, when locally available, can be used to construct a safe and efficient roadway rapidly and at relatively low cost, one or the other is often the preferred material for haul road surfacing at many mine sites. When constructed and maintained adequately, both materials offer a stable roadway that resists deformation and provides good traction with low rolling resistance. The required thickness of surfacing material, as well as the associated sub-base and base materials, can be determined from the CBR curves (Figure 3-3). A satisfactory gradation for granular surface materials is provided in Table 5-3. However, roads subject to freezing or prolonged inclement weather should not contain more than 10% fines (less than No. 200 US Standard sieve size) to prevent muddy, slippery conditions when wet or thawing. Those subject to hot, dry weather should contain at least 5% fines to minimize dust problems and surface loosening when dry. Granular surfacing should be free from loam, roots, organic matter, frozen lumps and other unsuitable material. The particles of the granular material should be clean, sound and durable. Gravel larger than 9.5mm should have 30% or more fractured faces. Granular surfacing material should be placed in lifts not exceeding 200mm in thickness prior to compaction. Each lift should be uniform in gradation and moisture content, spread without causing particle segregation and compacted with a vibratory smooth drum roller weighing at least 15mt. Each lift placed in the surface layer should also be compacted to a dry density of at least 98% of Standard Proctor maximum dry density.

Table 5-3 Recommended grading for granular material used in the surface layer (Monenco 1989).

| ASTM sieve size | % by weight passing |
|---|---|
| 76mm (3”) | 100 |
| 38mm (1.5”) | 70 – 100 |
| 25mm (1”) | 55 – 88 |
| 9.5mm (3/8”) | 40 – 70 |
| #4 | 30 – 55 |
| #10 | 22 – 42 |
| #200 | 5 – 10 |

Thompson and Visser (1997, 2000) presented results from haul road trafficability studies performed on roads in South Africa. They examined numerous functional performance indicators such as severity of potholes, corrugations, rutting, loose material, dustiness, loose and fixed stones, cracks, erosion, and skid resistance. These defects were correlated to surface material properties such as dust ratio, plasticity index, CBR, grading coefficient, shrinkage product as well as the maintenance cycle and daily tonnage hauled. Their research has led to the establishment of material specifications shown in Table 5-4 that are calibrated for mine haul roads. The ideal range for the shrinkage product is 95 to 130 while the ideal range for the grading coefficient is 25 to 32. Figure 5-1 shows the ideal and recommended range of two important material properties for the surface materials. The impacts of material properties outside the recommended range are also depicted in Figure 5-1.

Table 5-4 Recommended material properties for a haul road surface material (after Thompson & Visser 2000)

| Property | Min. | Max. | Impact on Functionality |
|---|---|---|---|
| Shrinkage product | 85 | 200 | reduce slipperiness but prone to ravel & corrugations |
| Grading coefficient | 20 | 35 | reduce erodibility but induce tendency to ravel |
| Dust ratio | 0.4 | 0.6 | reduce dust generation but induces ravelling |
| Liquid limit (%) | 17 | 24 | reduce slipperiness but prone to dust |
| Plastic limit (%) | 12 | 17 | reduce slipperiness but prone to dust |
| Plasticity index | 4 | 8 | reduce slipperiness but prone to dust |
| CBR at 98% Mod. AASHTO | 80 | | resist erosion, improve trafficability |
| Max. particle size (mm) | | 40 | ease maintenance, no tire damage |

Shrinkage product = bar linear shrinkage x P425

Grading coefficient = P265 - P2) x P475 / 100

Dust ratio = P075 / P425

Where P075, P425, P2, P475, and P265 refer the percent by weight passing sieves of size 0.075, 0.425, 2.0, 4.75, and 26.5mm respectively

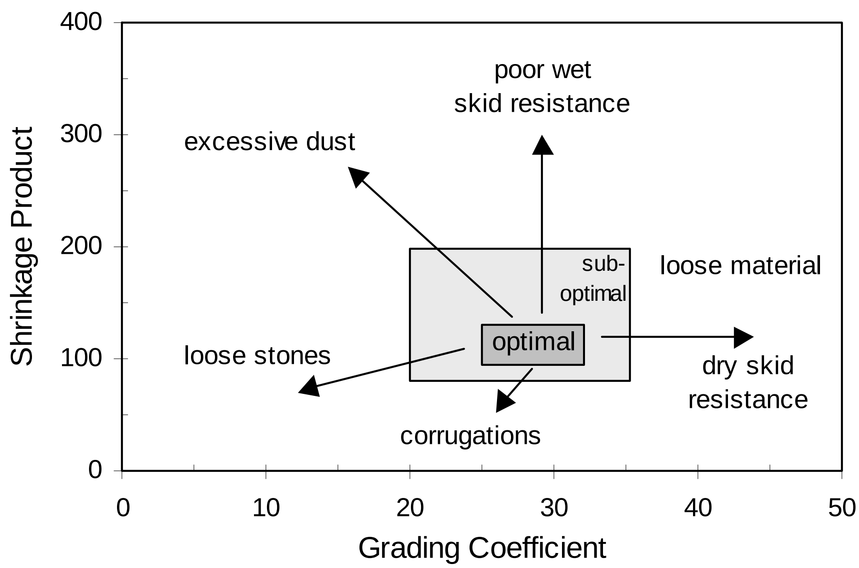


Figure 5-1 Optimal and sub-optimal range of values for the shrinkage product and grading coefficient for materials used on the road surface.

Other suitable materials that can be used in lieu of gravel or crushed rock include fine shot rock, scoria (vesicular lava), slag, cinders, volcanic ash, mill tailings and disintegrated granite or shale. Note that those materials containing more than the recommended fines content may necessitate increased road maintenance. In addition, volcanic ash, if altered by weathering, may be bentonic, which would cause slippery conditions when wet.

The natural loss of surface gravel should be replaced as part of the road maintenance program. New gravel should be blending into existing material by scarifying into the old surface and recompacting.

### 5.1.2 Asphaltic Concrete

Like rollcrete, asphaltic concrete exhibits a high coefficient of road adhesion and creates a surface that minimizes dust problems. In addition, the characteristic stability of this material creates a smooth haulage surface that can be travelled with little fear of encountering rut or potholes that would impede haul truck controllability. Should potholes or ruts occur, they could readily be corrected by patching. Kaufman and Ault (1977) state that:

“These surfaces are equally attractive from a production standpoint. While an increasing number of operators are beginning to utilize asphaltic concrete because of lower road maintenance costs, the smooth surface also allows haulage vehicles to travel safely at grater speeds. This speeds up the production cycle. A seasonal disadvantage to using this composition, however, is revealed during the first snow or freezing rain. The characteristically smooth surface of asphalt offers little resistance to development of an ice or snow glaze. Thus, the roadway can become extremely slick and remain so until corrective measures are employed. This could constitute a serious threat to operational safety in mining areas where rapid and frequent freeze conditions prevail.”

Being an engineered material, asphaltic concrete must be processed and applied within the constraints of good engineering practice. In order to be stable, the exact mix of aggregate and asphalt cement suitable for locally available materials should be obtained from provincial Highway Departments, paving contractors or consulting engineers experienced in pavement design. As with rollcrete construction, asphaltic concrete must be placed on an adequate thickness of well-compacted sub-base and base material. It is recommended that the base layer consist of crusted rock with a CBR of 90% or more. Kaufman and Ault (1977) indicate that, due to the high wheel loads imposed on the haul road surface, a 100mm layer of asphaltic concrete should be considered the minimum thickness for a surface layer. Shukla et al. (1989), in their studies on haul roads in India, have developed tentative empirical criteria for pavement thickness based on an equivalent wheel load driven from considerations of the pavement deflections under single and multiple-configuration wheel loads, respectively. Using these criteria, Monenco (1989) determined the total road fill thickness for various haul trucks and equivalent wheel loads (see Table 5-5).

Table 5-5 Critical road fill thickness for loaded trucks (after Monenco 1989).

| Haul truck capacity (tonnes) | Total fill thickness (cm) | Equivalent wheel load for loaded truck (kg) |
|---|---|---|
| 35 | 90 | 17,100 |
| 50 | 105 | 26,009 |
| 85 | 140 | 42,500 |
| 120 | 150 | 60,600 |
| 170 | 180 | 80,500 |

For a base layer having CBR = 80% or more, the thickness of asphaltic concrete to withstand one million wheel load applications is set out in Table 5-6.

Table 5-6 Thickness of asphaltic concrete for a base layer of CBR >80% (after Monenco 1989).

| Haul truck capacity (tonnes) | Asphaltic concrete thickness (cm) | |
|---|---|---|
| | Loaded truck | Unloaded truck |
| 120 | 27.5 | 17.5 |
| 170 | 32.5 | 17.5 |

Shukla et al. (1989) computed the relative costs of conventional haul roads with granular construction compared to haul roads with bituminous surfaces by making the following assumptions:

- bituminous roads require resurfacing every five years whereas granular construction requires a renewal coat every 6 months,
- haul truck fuel consumption on granular roads is 1.5 times higher than on bituminous roads,
- tire life on bituminous roads is double that on granular roads, and
- vehicle depreciation is less on bituminous roads.

Based on the above assumptions, Monenco (1989) estimated that, although the initial cost of bituminous roads is approximately 70% higher than granular roads, the cumulative discounted vehicle operation cost per 100 trucks on bituminous roads over a 20 year period is about 84% of the equivalent cost on granular roads. Because of resurfacing every five years, the maintenance cost for bituminous roads is about 6% higher than that for granular roads.

The estimated net savings amounted to the equivalent of $40 million.

Monenco (1989) conclude that bituminous pavements:

- can be designed and constructed by the same procedures used for less heavily loaded highways provided the heavier wheel loads on haul roads are taken into account,
- provide low rolling resistance and dust free service, and
- show cost savings when the cost of construction and maintenance are compared with cost of grading unpaved roads, fleet maintenance costs, tire costs, fuel costs, etc.

Because of the relatively high cost of asphaltic concrete surfaces, each mine operator must assess if the benefits of increased speed and reduced road maintenance will offset the high initial cost. The determining factors will generally be the length of haul and the required haul road life. If the road life is relatively short, an asphalt surface may be difficult to justify. On the other hand, if the haul road is long and is to be in service for a number of years, placement of asphaltic concrete may prove feasible (Kaufman & Ault 1977).

### 5.1.3 Roller Compacted Concrete

Roller-compacted concrete, or rollcrete, consists of pre-mixed concrete which is dumped on the roadbed, spread to a uniform thickness with a dozer or grader and compacted with a vibratory roller in the same manner utilized to compact rock fill. Although lift thickness for mass rollcrete can vary to 0.6m, road surface applications should be limited to individual lifts not exceeding about 0.3m. Water/cement ratios should be adjusted to produce a stiff, zero slump mix with 28-day uniaxial compressive strengths from 15MPa to 30MPa. Compared with conventionally formed concrete, the in-place cost of rollcrete is appreciably less (40% to 60%) because of placement efficiencies, high placement rates and the absence of labour-intensive formwork.

According to American Concrete Institute (ACI 1988), rollcrete must be placed in layers or lifts thin enough to allow complete compaction by the vibratory roller or place compactor. To date, field tests have indicated that optimum placement layers range from 0.2m to 0.3m. This contrasts to normal layers in conventional mass concrete of 0.46m to 0.60m. Considering the high placement rates attainable, several pieces of dumping and spreading equipment may be necessary to keep pace with one large vibratory roller. A 1.5m wide vibratory roller making four passes travelling at a speed of 3.25km/hr can compact more than $260m^3/h$ of zero-slump concrete in 0.25m layers. Generally, any vibratory roller that can successfully compact rockfill will compact rollcrete. Self-propelled rollers with power driven vibrating drums have proven more suitable for rollcrete than towed vibratory rollers.

Rollcrete produces a tough, hard, durable surface that, when properly smoothed by mechanical screeding and troweling, will exhibit a long-lasting smooth profile with low rolling resistance and high traction characteristics (see Table 4-1 and Table 4-4). Prior to placing the rollcrete, a sufficient thickness of compacted sub-base must be established, followed by an additional layer of compacted base materials to form the foundation for the rollcrete surfacing. No established procedure is available to determine the minimum thickness of rollcrete on heavily loaded haul roads. One approach would be to construct a trial rollcrete pad with varying thickness in a section of an existing road and monitor its behaviour for a couple of years. A similar procedure was adopted in 1988 at the Syncrude Canada Ltd. mine site when a trial pad 400m long by 25m wide was constructed with a uniform thickness of 0.6m for 170t trucks (Van Wieren & Anderson 1990). Although the thickness was arbitrarily chosen, 60% of the length was spread with a mechanized paver while a dozer was used for the remainder. After spreading, the rollcrete was compacted with a vibratory, smooth-faced, drum roller. The concrete mix consisted of minus 38mm crushed aggregate with 8% cement content by weight.

The rollcrete test section performed well but roller compacted concrete is relatively expensive and the road cannot be used for a number of days (2 weeks) until the concrete has cured. For rollcrete to function well it is imperative that the sub-grade be sufficiently stiff to prevent excessive straining in the rollcrete layer. For very large trucks, this may require placement of an engineered base layer of considerable thickness before application of the rollcrete.

## 5.2 Materials for Base and Sub-Base Layers

Base and sub-base layers are generally constructed from locally available materials, but stabilization of locally available materials is required when the design with current materials yields unacceptable thickness of layers and/or the suitable construction materials are uneconomic to use (due to distance or depth limitations or environment restrictions). Generally, pit run gravel is used for the base layer. The sub-base is often constructed from interburden, sand, silty or sandy till, or other suitable materials. Usually the materials used in base and sub-base layers are not crushed thus a particular particle size distribution is difficult to enforce. However, the maximum particle size should be limited to the 2/3 of the lift thickness. This can be achieved through screening or visual inspection.

### 5.2.1 Material Properties

The ability of a given sub-grade to support vehicular or other loading is termed its bearing capacity. Typical or assumed bearing capacity values for different sub-grade materials are listed in Table 5-7. However, determining the bearing capacity of a particular soil is a detailed procedure that should be carried out by a qualified geotechnical engineer. Since many haul trucks operate with tires inflated to 550kPa (80psi) or more, it can be seen from Table 5-7 that any material weaker than soft rock will require additional fill material to establish a stable road base. The designer must therefore determine the thickness and quality of additional material that should be placed over the sub-grade to adequately support the applied traffic loads.

Table 5-7 Approximate bearing capacity of various materials (Monenco 1989).

| Material | Bearing capacity (kPa) |
|---|---|
| Hard, sound rock | 5520+ |
| Medium hard rock | 2760-4140 |
| Hardpan overlying rock | 890-1240 |
| Dense gravel; very dense sand and gravel | 825-1100 |
| Soft rock | 690-825 |
| Medium dense to dense sand and gravel | 550-690 |
| Hard, dry over consolidated clay | 410-550 |
| Loose, coarse to medium sand, medium dense fine sand | 205-410 |
| Compact sand-clay soils | 205-275 |
| Loose fine sand, medium dense sand-silt soils | 100-205 |
| Firm or stiff clay | 68-135 |
| Loose saturated sand, medium soft clay | 34-68 |
| Muskeg, peats, marsh soils | 0-34 |
| Loose to medium dense mine spoil | 34-515 |

Table 5-8 shows the approximate properties of common haul road construction materials, which can be used for preliminary selection of material. The design of a haul road should be based on test results of local road construction materials, as these properties vary from source to source.

Table 5-8 Approximate properties of haul road construction materials.

| Materials | Young's Modulus (MPa) | Standard Proctor Density ($kN/m^3$) | Optimum Moisture Content (%) |
|---|---|---|---|
| Silt | 40[2] | 18[1] | 14[1] |
| Clay | | 19[1] | 14[1] |
| Siltstone (Crushed) | 40[3] | 18[3] | 12[3] |
| Sand | 80[2] | 16 – 17[4] | 10 – 13[4] |
| Limestone (Crushed) | | 20[1] | |
| Pitrun Gravel | 330[2] | 20 – 22[4] | 6 – 9[4] |
| Crushed Gravel | 330[2] | 21 – 22[4] | 6 – 8[4] |

[1]Courtesy Suncor
[2]Courtesy Syncrude
[3]Kumar (2000)
[4]Van Wieren and Anderson (1990)

The material selection depends mainly on the rigidity of the material or the Young's modulus. Stiffer materials require smaller cover thickness. Standard Proctor density is used for volume of material required and as a benchmark for the density achieved in a haul road. Maintenance of optimum moisture content is critical in achieving required density.

### 5.2.2 Fly Ash

Any soil that has been transformed from its natural state by special procedures or additives is known as stabilized earth. Within the haul road context, this generally means increasing the soil strength, stiffness and bearing capacity by incorporating cementing agents such as Portland cement, asphalt, fly ash, calcium chloride, ligno-sulfates or hydrated lime. Such treatment, however, will not generally improve native soils to the extent that they can be used as surfacing materials, but when applied to sub-grade, sub-base or base materials can often substantially reduce the quantity of road fill beneath the surface layer. An exception is fly ash exhibiting pozzolanic or self-cementing properties, which has been used on a trial basis at Highvale Mine. The fly ash was mixed in place on the road surface with poorly indurated sandstone spoil and gravel and subsequently compacted with loaded haul trucks. Performance of the stabilized surface was good.

Coal mines often do not have access to good road construction materials, given the clay-rich and weak nature of the sedimentary rocks associated with coal. For mines located within 100km of a coal-fired power plant, fly ash can be used as an economical cementing agent to improve the construction material characteristics. Cementing properties of fly ash depend on type of coal burned in the power plant. Fly ash, with a high percentage of CaO is self-cementing, while others may require supplementary CaO, usually from lime. Another source of CaO is kiln dust, which is a by-product of cement manufacturing.

Tannant and Kumar (2000) performed unconfined compression tests on various combinations of fly ash, kiln dust and road building aggregates at different ages of curing to measure compressive strength and modulus. Fly ash and aggregates were obtained from the Sundance power plant and adjoining Highvale Mine located west of Edmonton, Alberta. Cement kiln dust was obtained from the Lafarge Exshaw plant near Canmore, Alberta. Typically, the compressive strength of compacted aggregates increased from 0.09MPa to 0.9MPa due to addition of 24% of binder (20% fly ash and 4% kiln dust) after 14 days of curing. The Young’s modulus also increased from 30MPa to 300MPa. Lower percentage of binder and/or shorter curing period resulted in lower compressive strength and Young’s modulus. Sherwood and Ryley (1966) found similar compressive strengths for LFA mixes.

Laboratory tests demonstrate that fly ash cementing can increase both strength and stiffness of road construction materials. Thus, thinner layers may be used for road construction. Stiffer fly ash cemented base and sub-base layers will reduce deflections of the haul road cross-section thus reducing the rolling resistance.

There are three basic methods to place and mix lime, fly ash and aggregate (LFA). The components can be mixed in a concrete mixer and spread on the road with a grader. This method results in the best mixing and consequently better cementation. Another method is to dump lime and fly ash in a windrow on the road surface, and to use a grader to mix the LFA. This method does not provide good mixing of the components. A better method is to use the grader to spread the windrow in a 0.2 to 0.3m thick lift and then use a rototiller (or disc) to mix the LFA. In all cases, the LFA needs to be compacted using appropriate equipment (e.g., vibratory roller).

Zhou et al. (1997) reports use of dump trucks to deliver and spread fly ash and the use of a grader, agricultural disc, and agricultural rototiller for scarifying the existing road surface and mixing the road materials with fly ash to stabilize the top 0.3m and 0.6m of test sections on roads used to haul trees to the mill. A tamping foot compactor was used to compact the mixture. Clemmons (1983) reports use of asphalt batch plant to mix the fly ash, aggregates and lime for use in a base layer of a highway. The LFA was hauled by rear dump trucks and spread by grader. A 25t pneumatic tire and 12t vibratory roller were used for compaction.

The stiffest material should be placed in a haul road cross-section as near the surface as possible (Section 9.4). LFA should not be used as the surface layer as it is not as strong as concrete or RCC. Moreover, it is not as easy to maintain as crushed gravel. Thus, the greatest benefit from fly ash is realized by using by using 0.5m - 0.8m of LFA as a base layer for 360mt trucks, thus requiring 0.1m to 0.2m of LF for the construction.

### 5.3 Compaction Requirements

Good compaction contributes to material stiffness and strength. If compaction is not well executed at the construction stage, then subsequent traffic will complete the job, usually in a random manner, leading to deformation of the running surface and possible structural break down of the layered cross-section. Poor compaction in the lower layers cannot be fixed later by applying heavy compaction effort to the finished road or by road maintenance activities.

Once the depth of embankment fill and the thickness of the various sub-layers have been established for various sub-grade conditions along the proposed haul road route, proper placement procedures must be implemented. Kaufman and Ault (1977) state that, regardless of the material used, the sub-base, base and surface layers should be compacted in lifts not exceeding about 0.2m in thickness.

To ensure stability of the final road surface, the embankment fill materials should exceed the final desired surface width by at least 0.6m and must always be compacted while moist. Compaction equipment should preferably consist of heavy (15t), smooth-faced, vibratory rollers for cohesionless materials or sheep foot rollers of a similar weight for cohesive soils. Since few mine operators include such equipment in their fleet, use of loaded haul trucks or large dozers can be made to compact the road fill. Compaction of each 0.2m layer will require repeated passes (up to 6) of the compaction equipment until the soil no longer compresses under the weight of the vehicle. The finished surface is proof rolled to check the achieved compaction / suitability of the material used in the layer. It involves passing a fully loaded truck of specified size over the surface and measuring rut & roll. The rut & roll more than the limit (generally assumed to be between 5mm – 15mm), then further scarifying and recompacting, or bridging with suitable materials and compacting may be required. A suitable construction procedure is:

1. Proof roll the proposed road alignment with a loaded haul truck. Any soft or weak areas that are observed should be excavated to competent ground and backfilled with suitable material placed in 0.2m thick lifts and compacted to 95% of Standard Proctor maximum dry density. Compaction will probably require about six passes of a loaded haul truck.
2. After proof rolling, the top 0.15m of the roadbed sub-grade should be scarified and re-compacted to 95% of Standard Proctor using a sheeps foot or vibratory compactor.
3. The road sub-base will typically consist of granular material placed in 0.2m thick lifts compacted to 95% of Standard Proctor maximum dry density utilizing about 6 passes of a vibratory compactor.
4. The road base consists of well-graded gravel placed in 0.15m lifts and compacted to 98% of Standard Proctor maximum dry density using a smooth drum vibratory roller. The surface or wearing layer consists of a 0.3m to 0.5m thickness of well-graded crushed rock placed in 0.15m lifts and compacted to 98% of Standard Proctor maximum dry density using the

smooth drum vibratory roller. The surface layer compaction can be increased to 100% Proctor if required.

5. During road construction, continuously monitor compaction and moisture contents using a nuclear densometer. For each material used in the road there will be an optimum moisture content that will yield the highest density and hence, best resulting material properties. Therefore, the construction materials should be compacted near their optimum moisture contents. A small deviation from optimum water content is tolerable but wide deviations will lead to trouble.
6. Crown the completed road surface at about 2 to 3% slope to facilitate drainage and slope the road sides at 3H:1V.
7. Provide drainage ditches on both sides of the road to ensure good drainage.

# 6 HAUL ROAD ECONOMICS

## 6.1 Introduction

Haul road construction is a necessary cost in all surface mines that use mobile equipment. The cost of haul road construction varies in different types of mines and even from mine to mine in the same industry. Hard rock mines tend to have an abundance of sub-base and base materials, while soft rock mines must select good in-mine material, import or manufacture these materials. In almost all mines, materials for the surface layer must be imported and/or manufactured.

The economics of haul road construction are much more complicated than just calculating the cost of road construction. For a true understanding of haul road economics, full life-cycle costs must be considered, and include the following items:

- road construction costs,
- road removal costs,
- impact on fleet productivity and operating cost,
- differential road maintenance costs,
- extra fleet operating and maintenance costs ,
- extra stripping costs, and
- time value of money.

In most mines, road construction practices are based on previous practices rather than economics. In many cases, previous practices have produced cost-effective roads since they are based on experience and judgmental (empirical) background. For instance, mines tend to place temporary roads (low cost construction) to shovel faces, semi-permanent roads (medium cost construction) for main in-pit haul roads and permanent (higher cost construction) for out-of-pit haul roads. From a "time of use" perspective, this may make sense since economic analysis of haul road construction would indicate the same choices. However, the road type selection may not be optimized without a true economic evaluation.

This section outlines a means of calculating "life cycle economics" for mines that prefer to use this approach.

## 6.2 Costs Associated with Road Building

### 6.2.1 Pre-Road Construction Preparation

Sub-grade preparation varies greatly between mines and within different areas of a given mine. In hard rock mines, it is usually sufficient to grade the original ground. In other mines, such as oil sand mines, water, organic debris and weak materials may have to be removed before haul road construction begins.

Ditching is a necessity in almost all cases, since water must be kept to a minimum within the haul road construction material and the underlying base. Failure to keep water out of these materials will result in deterioration of the road. The size and shape of ditches will vary between different types of roads and different mines.

### 6.2.2 Road Construction Costs

Costs associated with actual haul road construction are quite simple to compute, providing appropriate costs are available. Simplistically, the haul road construction costs include the following:

- sub-grade preparation,
- sub-base material placement and preparation,
- base placement and preparation,
- surface material placement and preparation,
- berm placement, and
- ditching.

Road construction material consists of the following:

- run of mine waste,
- materials salvaged from other roads,
- material from stockpiles, and
- material imported from borrow pits.

If waste material that would have to be hauled in any case is used, then the cost of this material is the cost of moving and placing the material at the road location minus the cost to move and place it at the final waste location (dump). In many cases, this cost could be negative or a saving!

If the material is acquired from old roads, stockpiles or borrow pits, then the cost is the total of:

- mining,
- preparation (crushing, washing, etc),
- stockpiling (dumping, stacking and reclaiming), and
- hauling and dumping /preparation (spreading/compaction).

The cost of this type of material is usually real (and relatively high).

Berms are usually formed by free dumping of waste material. Consequently, berm construction cost is usually minimal or even negative (savings).

### 6.2.3 Road Removal Costs

Once the haul road is no longer needed, the road must be removed. The only exception is where roads are located on material that will never be mined (bottom of pit roads, out-of-pit final ramps, out-of-pit permanent roads). The cost of road removal will be the cost of mining, hauling and dumping of the road material plus any cost incurred due to dilution of ore or ore loss.

### 6.2.4 Fleet Productivity

The quality of the road construction will have a direct impact on the rolling resistance. The rolling resistance will have a direct impact on the speed of trucks and hence haul fleet productivity.

Temporary roads are usually of inferior construction and produce higher rolling resistance than other roads. These temporary roads are used for shovel and dump access and are short lived (measured in days or weeks). Rolling resistances will vary from 3% to 20% on these roads depending on the mine.

Semi-permanent roads tend to be better quality and consequently have less rolling resistance. The service life of semi-permanent roads is usually measured in weeks or months. Rolling resistances will vary from 3% to 10% depending on the mine.

Permanent roads tend to be of superior quality and consequently have the least rolling resistance. Permanent roads are usually used for many years. Rolling resistances of these roads vary from 1.5% to 5% depending on the mine.

Productivity losses caused by the different types of roads can be calculated by using readily available computer programs such as VESIM, or manually, by considering the rolling resistance, the length of road, and the return trip time of the haulage fleet.

Fleet productivity costs can then be calculated for different roads by applying the productivity loss to a fleet and calculating both the operating and capital cost impacts. The following example demonstrates the productivity impact.

> Assume a mine is considering a length of road that can be constructed to either a temporary or semi-permanent standard. If the productivity loss on the road is 5% (1 min. in a 20 min. return trip) then:
>
> Operating cost = fleet haulage costs + 5%
>
> Capital cost = Cost of extra haulage fleet to meet production
>
> The capital cost could be replaced by operating cost in the form of rental haulage equipment or contractor (for replacement of loss production). It should be noted that this cost applies for the life of the road involved and the portion of fleet using that road.

## 6.3 Road Maintenance

Differences in road maintenance can be quite large depending on the type of road. For example, temporary roads use less and poorer quality sub-base and base materials, thus rolling and rutting occur more frequently. Repair of this rolling and rutting is an on-going equipment requirement. Surface material is often lost and must be replaced on a regular basis.

## 6.4 Extra Fleet Operating and Maintenance Costs

The extra cost of operating a fleet on poor roads is real but hard to quantify. The extra rolling resistance of poor quality road increases fuel costs and reduces component life. The rolling and rutting of poor quality roads places strains on vehicles that will show up as frame cracking and reduced component life. However, trying to estimate the actual cost is very difficult.

Methods of quantifying these costs will range from “best judgement” through to extensive research. These costs are usually ignored, since most mines do not conduct extensive research and “best judgement” is hard to base costs on. But since this cost is a “real” cost, some allowance should be placed in the economic analysis. The most appropriate method is probably a percentage increase in operating/maintenance costs for fleet vehicles. For example, extra equipment cost for poor quality roads = regular cost of equipment x F, where F is an empirical factor between 1% and 10%.

## 6.5 Other Considerations

### 6.5.1 Climate

Climate can have a major influence on the quality of roads that are needed. In cold climates, roads tend to freeze in the winter and construction and maintenance are minimal during this period. Consequently, any road used only in sub-freezing weather can be constructed at minimal specifications. As long as the temperature is such that the material in and under the road freezes, minimal materials need to be placed.

In arid areas, road materials can be of a lower specification since there will be little or no water saturation of the road material. However, roads experiencing high precipitation will usually require higher quality road materials and extensive drainage systems.

### 6.5.2 Application of Larger Trucks

The mining industry continues to move towards larger and larger haul trucks to cut operating costs. However, larger trucks usually require better and wider roads. The impact of these roads is not always considered when reviewing the economics of larger trucks.

Many mines establish their road width by using criteria that relate the width of the truck to the width of the road. In most cases, road widths are designed at 3 to 4 times the width of the truck. If the criterion is 4 times the width of a truck, each extra metre of truck width will result in a road 4m wider. The direct impact of the road construction is the extra 4m-construction cost for the wider road.

Another cost that is especially significant in deep open pit mines, is the increased stripping (or loss of ore) that wider roads cause. For instance, if a haul truck that is 1m wider is chosen and the criteria for roads is 4 times the truck width, every metre of truck width will result in the stripping of 4 extra metres width above the road.

**Simplistic Example:**

Assume that the ultimate pit of a mine is 300m deep and the final ramp is 10% grade and makes one full circle of the pit wall. Net road construction costs are $\$10/m^2$ and maintenance costs are $\$5/m^2$ per year. Average stripping costs are \$2/bcm and life of mine is 10 years.

Therefore, the ramp will be 3000 metres long. If a truck is chosen that is 1m wider than the alternative and the road width = 4 x truck width, then the mine incurs the following costs over its life span.

Extra construction costs = length of road x extra width x const. cost per $m^2$

$$3000m \times 4m \times \$10/m^2 = \$120,000$$

Extra maintenance cost = avg. length of road x extra width x mnt. cost/$m^2$/yr x 10yr

$$1500m \times 4m \times \$5/yr \times 10yrs = \$300,000$$

Extra strip costs = avg. depth of road x length of road x extra width x stripping cost

$$300m / 2 \times 3000m \times 4m \times \$2/bcm = \$3.6M$$

Therefore the mine-life cost of the wider road incurred through the use of a larger haul trucks is \$4.02M (close to the cost of a large truck!).

For economic analysis, a cash flow sheet would be compiled and costs allocated on a yearly basis. An appropriate discount factor would be applied and a Net Present Cost calculated to apply against identified savings from the use of larger haulage trucks.

## 6.6 Comparison of Temporary and Semi-Permanent Roads

To illustrate the economics of the different roads, it is best to look at an example comparing a short section of temporary versus semi-permanent road connected to a main haul road. The temporary road is built with lower construction standards and thus has higher rolling resistance.

A mine must construct a 300m long and 30m wide road from the main haul road to a shovel face. This road has a service life of two weeks. The shovel will have four 240t trucks assigned to it. Truck productivity is estimated at 400 bcm/hr for good roads (including semi-permanent section) based on 4 trips per hour. The shovel will have a running time of 90%.

### 6.6.1 Temporary Road

Construction costs

Construction costs is a total of base preparation, base (1m thick) and surfacing (average of 0.1m thick). Assume base preparation at \$2/m$^2$, base material (waste from shovel dumped 2km short) at minus (-)\$0.40/bcm, and surface material at \$20/bcm.

| | |
|---|---|
| Base prep: 300m x 30m x \$2/m$^2$ | \$ 18.0K |
| Base: 300m x 30m x 1m x \$-0.4/bcm | \$ - 3.6K |
| Surface material: 300m x 30m x 0.1m x \$20/bcm | <u>\$ 18.0K</u> |
| Total construction cost | \$ 32.4K |

Maintenance costs

Assume ½ grader @ \$100/hr and 20% surface material replacement.

| | |
|---|---|
| Cost grading: 24hr/day x 14days x 90% x 0.5grader x \$100/hr | \$15.1K |
| Repairs: \$18.0K x 20% | <u>\$ 3.6K</u> |
| Total maintenance cost | \$18.7K |

Removal Cost

| | |
|---|---|
| Assume \$3/bcm to remove road: 300m x 30m x 1.1m x \$3/bcm | \$ 29.7K |

Productivity lost

The impact of using a temporary road versus a semi-permanent road design is assumed to be an increase in travel cycle time of 1.2 minutes. Therefore, productivity loss would be 1.2/15 = 8%. Assume these hours are replaced by rental trucks @ \$300/hr to maintain the same productivity.

| | |
|---|---|
| Cost = truck hours x % loss x cost per hour | |
| 24hr/day x 14days x 4trucks x 90% x 8% x \$300/hr | \$ 29.0K |

| | |
|---|---|
| Total life cost of temporary road | **\$109.8K** |

### 6.6.2 Semi-Permanent Road

Assume the semi-permanent road has 1m sub-base (cost the same as the base material for the temporary road), 1m better quality base, 0.1m surface gravel, and ditching. The sub-base will come from the shovel, but the base material will be imported from another shovel at zero cost basis (same haul as to dump) but a $3/m$^3$ placement cost. Productivity loss will be zero. Maintenance cost will be 15% of temporary road.

| | |
|---|---|
| Construction costs | |
| Costs base prep: 300m x 30m x $2/m$^2$ | $ 18.0K |
| Ditching: 300m x 2 x $2/m | $ 1.2K |
| Sub-base: 300m x 30m x 1m x $-0.4/bcm | $ -3.6K |
| Base: 300m x 30m x 1m x $3/bcm | $ 27.0K |
| Surface material: 300m x 30m x 0.1m x $20/bcm | $ 18.0K |
| Total construction cost | $ 60.6K |
| Maintenance costs | |
| Temporary road maint. cost x 15% ($18.7 x 0.15) | $ 2.8K |
| Removal cost | |
| Remove 2.1m thick @ $3/m$^3$ (300m x 30m x 2.1m) x $3/bcm | $56.7K |
| Productivity loss | $ 0.0K |
| Total life cost of semi-permanent road | **$ 120.1K** |

### 6.6.3 Conclusion

While total costs for each road option are similar, for the conditions chosen, the temporary road is the best choice although the rolling resistance is higher and cycle times are longer. There is a total of $10.3K ($120.1K - $109.8K) advantage of the temporary road over the semi-permanent road in this case for 2 weeks. Because the time duration is so short, there is no advantage to applying a discount rate to find a NPV.

From this example, it becomes apparent that the removal costs, the length of time in place, the number of trucks using the road, and the length of road are key factors in the road economics.

Road Removal. If the road did not have to be removed, the economics would change to favour the semi-permanent road.

Time of Use. The longer the road is in use, the more impact productivity costs, road maintenance cost and truck maintenance cost will have.

Number of trucks. The more trucks using the road, the greater the loss of production and the higher the maintenance costs.

If the road were longer, the semi-permanent road would save on:

- Productivity: productivity differential in speed would be much greater for a longer road, probably in the range of 20 to 30km/hr.
- Road maintenance: the road maintenance cost would increase linearly with length.
- Truck maintenance: truck maintenance cost would increase linearly with length.

Note, if the road has to be removed, it may still be economic to build a semi-permanent road if the cumulative maintenance and productivity savings are more than the removal cost. Also, if the removal is not for several years, the Net Present Value (NPV) of the semi-permanent road may be favourable although the total savings do not exceed the removal costs. This condition can occur when the savings accumulate early and the removal costs are incurred several years later. In this case, the NPV of the savings would be greater than the Net Present Cost of construction and removal.

## 6.7 Example of Full Life Cycle Economics Applied to a Haul Road

A mine is building a 1000m road in its pit that will carry half of its yearly production. The road will last for 2 years and will be removed at the end of that time. The following criteria are used:

| Roads: | Temporary | Semi-Permanent |
|---|---|---|
| Width | 30m | 30m |
| Surface material | 0.2m | 0.2m |
| Base prep | rough grading | fine grading and compaction |
| Sub-base | 0 | 2m |
| Base | 1m R.O.M. | 1m select |
| Ditching | 0 | 2 ditches |
| Road maintenance | heavy | medium (10% Temp) |
| Productivity | -5% | 0 % |
| Truck costs | $4 /hr | 0 |
| Removal cost | $3/bcm | $3/bcm |

Production rate 52M bcm/yr (6000 bcm/hr) with 20 available trucks. Discount Rate 15%.

### 6.7.1 Temporary Road

| | |
|---|---|
| **Construction cost** | |
| Base prep (area of 1000m x 30m) @ $1/sq. m | $ 30K |
| Base (credit of $0.4/m$^3$ | $ -12K |
| Surface material @ $20/m$^3$ | $ 120K |
| Berms @ 8m$^3$/m (credit of $0.4/m$^3$) | $ 3K |
| Total | $ 141K |
| **Road maintenance (per year)** | |
| Grading / dozing @ $100/hr | $ 876K |
| Repair (replace 20% of surface material) | $ 24K |
| Total | $ 900K |
| **Productivity cost (per year)** | |
| 5% reduced productivity @ $3/bcm replacement | $3900K |
| **Truck maintenance costs (per year)** | |
| Costs of 10 trucks @ 8760 hrs @ $4/hr | $ 350K |
| **Road removal costs** | |
| Removal costs @ $3/m$^3$ ($30K + $6K + $8K) | $ 132K |

### 6.7.2 Semi-permanent Road

Construction cost

| | |
|---|---|
| Base prep (area of 1000m x 30m) @ $\$2/m^2$ | \$ 60K |
| Sub-base (credit of $\$0.4/cm^3$) | \$ -24K |
| Base (selective from other shovel @ $\$1/m^3$) | \$ 30K |
| Surface Material @ $\$20/m^3$ | \$120K |
| Berms @ $8m^3/m$ (credit of $\$0.4/m^3$) | \$ 3K |
| Total | \$ 189K |

Road maintenance (per year)

| | |
|---|---|
| Grading / dozing @ 20% temp. | \$ 175K |
| Repair (replace 5% of surface material) | \$ 6K |
| Total | \$ 181K |

Productivity cost (per year)

| | |
|---|---|
| 0% reduced productivity | \$ 0K |

Truck maintenance costs (per year)

| | |
|---|---|
| Costs of 10 trucks @ 8760hrs @ \$0/hr | \$ 0K |

Road removal costs

| | |
|---|---|
| Removal costs @ $\$3/m^3$ | \$ 312K |

It is obvious by the productivity loss that the semi-permanent road is the right selection. However, to find the NPV of the semi-permanent over the temporary road, the following cash flow is developed from differential costs.

| Year | 0 | 1 | 2 |
|---|---|---|---|
| Construction | -\$48K | | |
| Operating costs | | +\$4969K | + \$4969K |
| Road removal | | | - \$ 180K |
| Total | -\$ 48K | +\$4969K | + \$4789K |
| Discount factor | 1 | 0.8696 | 0.7562 |
| Discounted cash flow | -\$ 48K | +\$4321K | + \$3621K |

NPV of semi-permanent versus permanent road = \$ 7.9 million dollars.

## 6.8 Summary

From an economic perspective, temporary, semi-permanent, and permanent all have application in most surface mines. Costs, road life and utilization impact the selection of road type. The selection of road type can be confirmed by an economic evaluation. However, a good costing system must be in place to allow this economic evaluation to be accurate.

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# APPENDICES

# 8 HAUL TRUCKS AND TIRES

## 8.1 Haul Trucks

Haul trucks used in surface mines have grown significantly in terms of size and capacity. In 1989, the largest trucks available were of 218mt capacity, but by 1999, the capacity has risen to more than 300mt. The physical dimensions of these trucks are in the order of 7m x 9m x 14m (height x width x length). Considering the fact that increases in the size of haul trucks were virtually at a stand still during the early half of the this decade, (due to the inadequacy of tire technology for larger trucks), this recent increase in haul truck size is significant. Larger haul trucks are being designed, produced, and accepted by the industry for one important reason: economy of scale.

Almost all of the large haul trucks in current use have two axles (with four tires on the rear axle). The use of two axles provides better manoeuvrability and smaller steering radius. The limiting factor in the design of larger haul trucks is the design of tires that match the trucks.

Now, manufacturers of haul trucks are planning for gross weights of more than 500mt (payload of more than 300mt). Correspondingly, the load per tire has increased to more than 85 tonnes. Tire pressure has also gone up to 827kPa (120psi) from 551kPa (80psi) during last five years. However, the new low profile truck tires (55/80R63, low profile) have an inflation pressure of 600kPa (87psi).

Table 8-1 and Table 8-2 shows the specifications of large Caterpillar haul trucks that are currently being used. Table 8-3 gives specifications for a variety of large trucks. These data were gathered from various sources and the table is incomplete.

The larger physical size of the trucks has an impact on road design. For example, the average turning radius of the trucks has increased by 10% over that of a generation earlier. For example, CAT 793C has a turning radius of 15m but CAT 797 has a turning radius of 16 m. The increase in turning radius has occurred as the truck length increased from 12.86m for CAT 793C to 14.5m for CAT 797. So, greater turning radius and width of road is required to accommodate these trucks. More importantly, the maximum speed of these trucks has increased in most cases by 8 to 10 kilometres per hour. For example, TI 252 and T 262 trucks by Liebherr have a maximum speed of 51km/hr whereas next generation trucks from same company, namely the TI 272 and T 282, have a maximum speed of 68 and 64km/hr respectively. This also has impact on the haul road geometry in terms of stopping distance. Other haul road dimensions would also have to increase to accommodate these larger trucks.

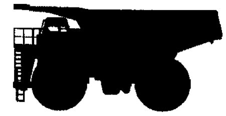
Table 8-1 Specifications of Caterpillar 777D and 785C trucks (Caterpillar 1999).

| **MODEL** | **777D** | | **777D** | | **785C** | |
|---|---|---|---|---|---|---|
| Body Type | **Flat Floor** | | **Dual Slope** | | **Dual Slope** | |
| Gross Vehicle Weight | 161 030 kg | **355,000 lb** | 161 030 kg | **355,000 lb** | 249 480 kg | **550,000 lb** |
| Chassis Weight* | 48 580 kg | **107,100 lb** | 48 580 kg | **107,100 lb** | 74 470 kg | **164,860 lb** |
| Body Weight | 16 430 kg | **36,185 lb** | 15 780 kg | **34,785 lb** | 21 260 kg | **46,860 lb** |
| Maximum Payload** | 96 020 kg | **211,710 lb** | 96 670 kg | **213,110 lb** | 153 760 kg | **338,970 lb** |
| Standard Liner Weight | 5675 kg | **12,500 lb** | 5460 kg | **12,040 lb** | 7630 kg | **16,830 lb** |
| Payload with Standard Liner | 90 340 kg | **199,210 lb** | 91 210 kg | **201,070 lb** | 146 120 kg | **322,140 lb** |
| Capacity: | | | | | | |
| Struck (SAE) | 42.0 $m^3$ | **54.6 $yd^3$** | 42.1 $m^3$ | **55 $yd^3$** | 56.9 $m^3$ | **74.4 $yd^3$** |
| Heaped (2:1) (SAE) | 60.5 $m^3$ | **79.1 $yd^3$** | 60.1 $m^3$ | **78.6 $yd^3$** | 78.2 $m^3$ | **102.3 $yd^3$** |
| Distribution Empty: | | | | | | |
| Front | **45.4%** | | **45.4%** | | **47%** | |
| Rear | **54.6%** | | **54.6%** | | **53%** | |
| Distribution Loaded: | | | | | | |
| Front | **33.3%** | | **33.3%** | | **33.3%** | |
| Rear | **66.7%** | | **66.7%** | | **66.7%** | |
| Engine Model | **3508BTA** | | **3508BTA** | | **3512BTA** | |
| Number of Cylinders | **8** | | **8** | | **12** | |
| Bore | 170 mm | **6.7"** | 170 mm | **6.7"** | 170 mm | **6.7"** |
| Stroke | 190 mm | **7.5"** | 190 mm | **7.5"** | 190 mm | **7.5"** |
| Displacement | 34.5 L | **2105 $in^3$** | 34.5 L | **2105 $in^3$** | 51.8 L | **3158 $in^3$** |
| Flywheel Power | 699 kW | **938 hp** | 699 kW | **938 hp** | 1005 kW | **1348 hp** |
| Gross Power | 746 kW | **1000 hp** | 746 kW | **1000 hp** | 1082 kW | **1450 hp** |
| Standard Tires | **27.00R49** | | **27.00R49** | | **33.00R51** | |
| Machine Clearance Turning Circle | 28.4 m | **93'2"** | 28.4 m | **93'2"** | 30.6 m | **100'4"** |
| Fuel Tank Refill Capacity | 1137 L | **300 U.S. gal** | 1137 L | **300 U.S. gal** | 3218 L | **850 U.S. gal** |
| Top Speed (Loaded) | 60 km/h | **38 mph** | 60 km/h | **38 mph** | 54 km/h | **33.6 mph** |
| **GENERAL DIMENSIONS (Empty):** | | | | | | |
| Height to Canopy Rock Guard Rail | 5.00 m | **16'5"** | 4.95 m | **16'3"** | 5.77 m | **18'11"** |
| Wheelbase | 4.57 m | **15'0"** | 4.57 m | **15'0"** | 5.18 m | **17'0"** |
| Overall Length | 9.78 m | **32'1"** | 9.78 m | **32'1"** | 11.02 m | **36'2"** |
| Loading Height (Empty) | 4.34 m | **14'3"** | 4.29 m | **14'1"** | 4.97 m | **16'4"** |
| Height at Full Dump | 9.97 m | **32'9"** | 9.95 m | **32'8"** | 11.21 m | **36'9"** |
| Body Length (Target Length) | 6.95 m | **22'10"** | 6.95 m | **22'10"** | 7.65 m | **25'1"** |
| Width (Operating) | 6.10 m | **20'0"** | 6.10 m | **20'0"** | 6.64 m | **21'4"** |
| Width (Shipping)*** | 3.51 m | **11'5"** | 3.51 m | **11'6"** | 3.91 m | **12'10"** |
| Front Tire Tread | 4.17 m | **13'8"** | 4.17 m | **13'8"** | 4.85 m | **15'11"** |

*Weights include lubricants, coolants and 10% fuel.
**Maximum rating requires selection of proper tires and is dependent on selection of optional equipment. Gross vehicle weight should not be exceeded.
***Disassembled.

Table 8-2 Specifications of Caterpillar 789C, 793C and 797 trucks (Caterpillar 1999).





| **MODEL** | **789C** | | **793C** | | **797** | |
|---|---|---|---|---|---|---|
| Body Type | **Dual Slope** | | **Dual Slope** | | | |
| Gross Vehicle Weight | 317 520 kg | **700,000 lb** | 376 490 kg | **830,000 lb** | 555 990 kg | **1,230,000 lb** |
| Chassis Weight* | 95 220 kg | **209,930 lb** | 113 510 kg | **250,250 lb** | 180 200 kg | **396,430 lb** |
| Body Weight | 26 280 kg | **57,940 lb** | 31 140 kg | **68,650 lb** | 50 460 kg | **111,010 lb** |
| Maximum Payload** | 196 010 kg | **432,130 lb** | 231 840 kg | **511,110 lb** | 326 530 kg | **718,370 lb** |
| Standard Liner Weight | 9430 kg | **20,790 lb** | 11 050 kg | **24,360 lb** | — | |
| Payload with Standard Liner | 186 580 kg | **411,340 lb** | 220 785 kg | **486,740 lb** | — | |
| Capacity: | | | | | | |
| Struck (SAE) | 73.4 m³ | **96 yd³** | 96 m³ | **126 yd³** | 173 m³ | **228 yd³** |
| Heaped (2:1) (SAE) | 105 m³ | **137 yd³** | 129 m³ | **169 yd³** | 220 m³ | **290 yd³** |
| Distribution Empty: | | | | | | |
| Front | **47%** | | **47%** | | **43.5%** | |
| Rear | **53%** | | **53%** | | **56.5%** | |
| Distribution Loaded: | | | | | | |
| Front | **33.6%** | | **33.6%** | | **33%** | |
| Rear | **66.4%** | | **66.4%** | | **67%** | |
| Engine Model | **3516BTA** | | **3516BTA** | | **3524BTA** | |
| Number of Cylinders | **16** | | **16** | | **24** | |
| Bore | 170 mm | **6.7"** | 170 mm | **6.7"** | 170 mm | **6.7"** |
| Stroke | 190 mm | **7.5"** | 190 mm | **7.5"** | 215 mm | **8.5"** |
| Displacement | 69 L | **4211 in³** | 69 L | **4211 in³** | 117 L | **7130 in³** |
| Flywheel Power | 1335 kW | **1791 hp** | 1615 kW | **2166 hp** | 2406 kW | **3227 hp** |
| Gross Power | 1417 kW | **1900 hp** | 1715 kW | **2300 hp** | 2535 kW | **3400 hp** |
| Standard Tires | **37.00R51** | | **40.00R57** | | **55/80R63** | |
| Machine Clearance Turning Circle | 30.2 m | **99'2"** | 32.6 m | **106'11"** | 31.9 m | **104'8"** |
| Fuel Tank Refill Capacity | 3218 L | **850 U.S. gal** | 3790 L | **1000 U.S. gal** | 6813 L | **1800 U.S. gal** |
| Top Speed (Loaded) | 52.57 km/h | **32.7 mph** | 53.6 km/h | **33.3 mph** | 64 km/h | **40 mph** |
| **GENERAL DIMENSIONS (Empty):** | | | | | | |
| Height to Canopy Rock Guard Rail | 6.15 m | **20'2"** | 6.43 m | **21'1"** | 7.24 m | **23'9"** |
| Wheelbase | 5.70 m | **18'8"** | 5.90 m | **19'4"** | 7.20 m | **23'7"** |
| Overall Length | 12.18 m | **39'11"** | 12.87 m | **42'3"** | 14.53 m | **47'8"** |
| Loading Height (Empty) | 5.21 m | **17'1"** | 5.86 m | **19'3"** | 7.05 m | **23'1"** |
| Height at Full Dump | 11.90 m | **39'1"** | 13.21 m | **43'4"** | 15.00 m | **49'3"** |
| Body Length (Target Length) | 8.15 m | **26'9"** | 8.94 m | **29'4"** | 14.46 m | **47'5"** |
| Width (Operating) | 7.67 m | **25'2"** | 7.41 m | **24'4"** | 9.15 m | **30'0"** |
| Width (Shipping)*** | 3.84 m | **12'7"** | 3.91 m | **12'10"** | 4.02 m | **13'2"** |
| Front Tire Tread | 5.43 m | **17'10"** | 5.61 m | **18'5"** | 6.60 m | **21'8"** |

*Weights include lubricants, coolants and 10% fuel.
**Maximum rating requires selection of proper tires and is dependent on selection of optional equipment. Gross vehicle weight should not be exceeded.
***Disassembled.

Table 8-3 Specifications of large haul trucks (not all data were available).

| Make | Model No. | GVW (mt) | Capacity mt | Capacity m$^3$ | Tires | Turning radius (m) | Loading height empty (m) | Width (m) | Length (m) | Axial weights (mt) Empty Front | Axial weights (mt) Empty Rear | Axial weights (mt) Loaded Front | Axial weights (mt) Loaded Rear | Max speed (km/hr) | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Caterpillar | Cat 785 | 249 | 136 | | | 15.3 | | | | | | | | | Caterpillar (1999) |
| Caterpillar | Cat 789 | 318 | 196 | 105 | 37.00R51 | 15.1 | 5.21 | 7.67 | 12.18 | 57 | 65 | 107 | 211 | 52.6 | Caterpillar (1999) |
| Caterpillar | Cat 793 | 377 | 232 | 129 | 40.00R57 | 16.3 | 5.86 | 7.41 | 12.87 | 69 | 78 | 127 | 250 | 53.6 | Caterpillar (1999) |
| Caterpillar | Cat 797 | 556 | 323 | 220 | 55/80R63 | 16.0 | 7.05 | 9.15 | 14.53 | xx | xx | 183 | 372 | 64.0 | Caterpillar (1999) |
| Euclid | 120E | 190 | | | | 11.6 | | | | | | | | | Euclid (undated) |
| Euclid | R-170 | 255 | | | | 13.3 | | | | | | | | | Euclid (undated) |
| Euclid | CH-150 | 229 | | | | 12.5 | | | | | | | | | Euclid (undated) |
| Komatsu | 830 E | 386 | 218 | 147 | 40.00R57* | 14.2 | 6.71 | 6.86 | 13.51 | 76.5 | 77.8 | 128.0 | 257.8 | 56.9 | Komatsu (1999) |
| Komatsu | 930 E | 480 | 290 | 184 | 50/90R57 | 12.4 | 6.68 | 8.10 | 15.24 | 92.7 | 97.6 | 160.1 | 320.2 | 64.5 | Komatsu (1999) |
| Kress | CH-160 | 207 | | | | 9.5 | | | | | | | | | Monenco Files |
| Liebherr | TI 252 | 325 | 195 | 108 | 37.00x57 | 12.3 | 5.6 | 7.1 | 13.3 | 53.5 | 76 | 107 | 217 | 51 | Liebherr brochure |
| Liebherr | T 262 | 370 | 218 | 119 | 40.00R57 | 14.2 | 5.9 | 7.4 | 13.3 | 68.5 | 83.5 | 122 | 248 | 51 | Liebherr brochure |
| Liebherr | TI 272 | 411 | 270 | 164 | 44/80R57 | 16.3 | 6.2 | 7.9 | 13.7 | 64 | 74.4 | 127.3 | 283.2 | 68 | Liebherr brochure |
| Liebherr | T 282 | 529 | 327 | 174 | 55/80R63 | 16.4 | 6.5 | 8.7 | 14.5 | 99 | 102 | 188.3 | 340.3 | 64 | Liebherr brochure |
| Terex | 34-11C | 218 | | | | 12.5 | | | | | | | | | Monenco Files |
| Terex | 33-15B | 260 | | | | 14.1 | | | | | | | | | Euclid (undated) |
| Unit Rig | MT 4400 | 392 | 236 | 139 | 40.00R57* | 12.6 | 6.6 | 7.4 | 13.9 | 74.1 | 82.2 | 130.8 | 261.5 | 59 | Unit Rig brochure |
| Unit Rig | MT 5500 | 510 | 308 | 181 | 55/80R63 | | 6.7 | 9.05 | 14.77 | 96.9 | 104.9 | 170.1 | 340.1 | | Unit Rig brochure |
| Unit Rig | Mark 36 | 249 | | | | 12.6 | | | | | | | | | Unit Rig brochure |
| Wabco | 120E | 190 | | | | 11.6 | | | | | | | | | Euclid (undated) |
| Wabco | 120C | 189 | 109 | 181 | 55/80R63 | 9.0 | 6.7 | 9.05 | 14.77 | 96.9 | 104.9 | 170.1 | 340.1 | 64.5 | Euclid (undated) |
| Wabco | 170 | 268 | 154 | | | | | | | | | | | | Euclid (undated) |

*Both radial and bias ply tires can be used

## 8.2 Rimpull-Speed-Gradeability Curves

The maximum speed attainable, gear range and available rimpull can be determined when the truck weight and total effective grade (or total resistance) is known. Rimpull is the force available between the tire and the ground to propel the machine (limited by traction). Weight is defined as gross vehicle weight (kg or lb) = truck + payload. For uphill hauls, the total effective grade (or total resistance) is grade resistance *plus* rolling resistance expressed as percentage grade. Grade is measured or estimated. Rolling resistance is estimated. A rolling resistance of 10kg/mt (20lb/t) = 1% adverse grade.

For example, with a 6% grade and a rolling resistance of 40kg/mt, the total resistance = 4% rolling + 6% grade = 10%.

To determine gradeability performance, use the following procedure. Read from gross weight down to the percentage of total resistance. (Total resistance equals actual % grade *plus* 1% for each 10kg/mt of rolling resistance.) From this weight-resistance point, read horizontally to the curve with the highest obtainable speed range, then down to the maximum speed. The usable rimpull depends upon the road traction and the weight on the drive wheels.

Example:

A 793C haul truck with an estimated GVW of 300,000kg is operating on a total effective grade of 10%. Find the available rimpull and maximum attainable speed.

From Figure 8-1 read from 300,000kg on gross weight scale down the line to the intersection of the 10% total resistance line. Go across horizontally to the rimpull scale on the left. This gives the required rimpull: 30,000kg. Where the line cuts the speed curve, read down vertically to obtain the maximum speed attainable for the 10% effective grade: 17km/hr. Therefore, the haul truck will climb the 10% effective grade at a maximum speed of 17km/hr in 3$^{rd}$ gear. The available rimpull is 30,000kg.

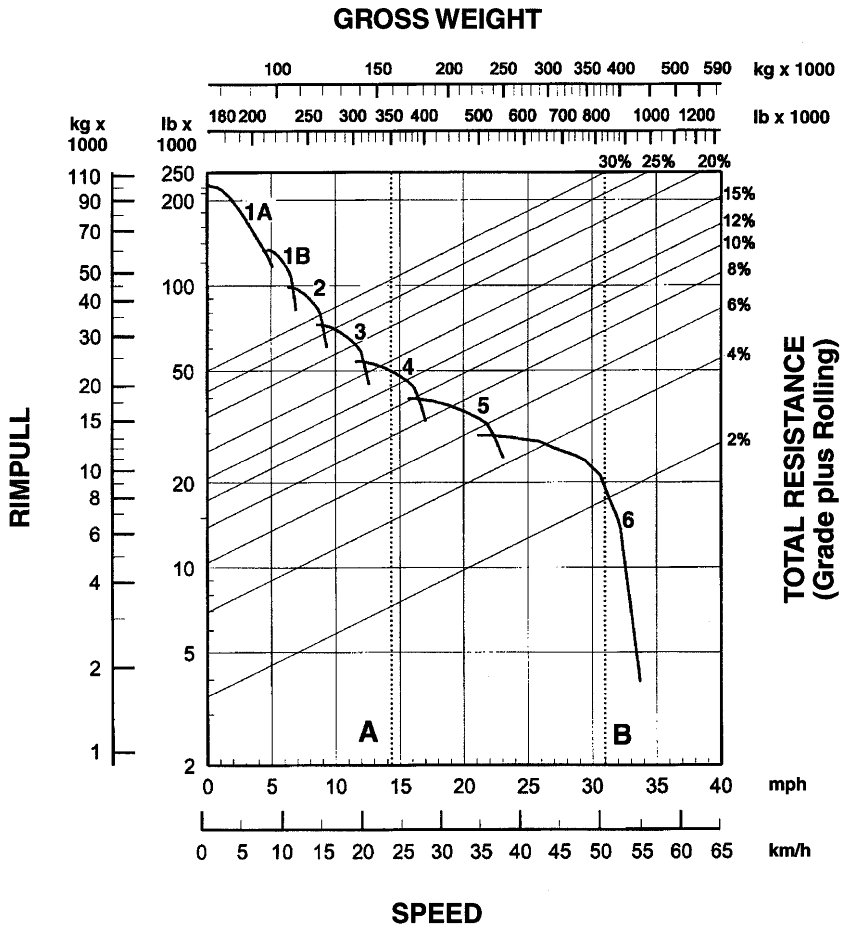



Figure 8-1 793C Rimpull-speed-gradeability, 40.00R57 Tires, 1778mm tire radius, A- estimated max. field empty weight, B- max. GVW (Caterpillar 1999).

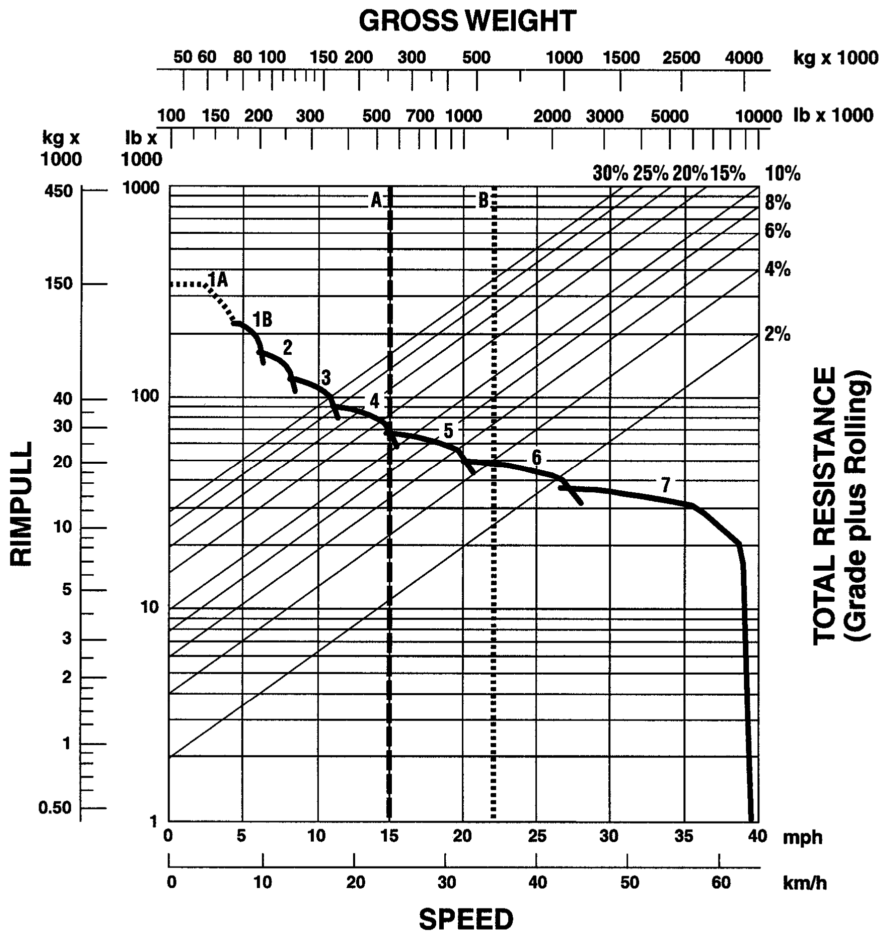



Figure 8-2 797 Rimpull-speed-gradeability, 55/80R63 Tires, A- estimated max. field empty weight, B- max GVW (Caterpillar 1999).

## 8.3 Haul Truck Retarder Curves

The speed that can be maintained when the truck is descending a grade with retarder applied can be determined from the retarder curves when the gross machine weight and total effective grade are known. As a typical example, Figure 8-3 and Figure 8-4 for a 793C haul truck (Caterpillar 1999) are presented. Select the appropriate grade distance chart that covers the total downhill haul; do not break the haul into individual segments.

To determine brake performance, use the following procedure. Read from gross weight down to the percent effective grade. Effective grade equals actual grade *minus* 1% for each 10kg/mt of rolling resistance. From this weight-effective grade point, read horizontally to the curve with the highest obtainable speed range, then down to maximum descent speed brakes can safely handle without exceeding cooling capacity. When braking, engine RPM should be maintained at the highest possible level without over speeding. If cooling oil overheats, reduce ground speed to allow transmission to shift to next lower speed range.

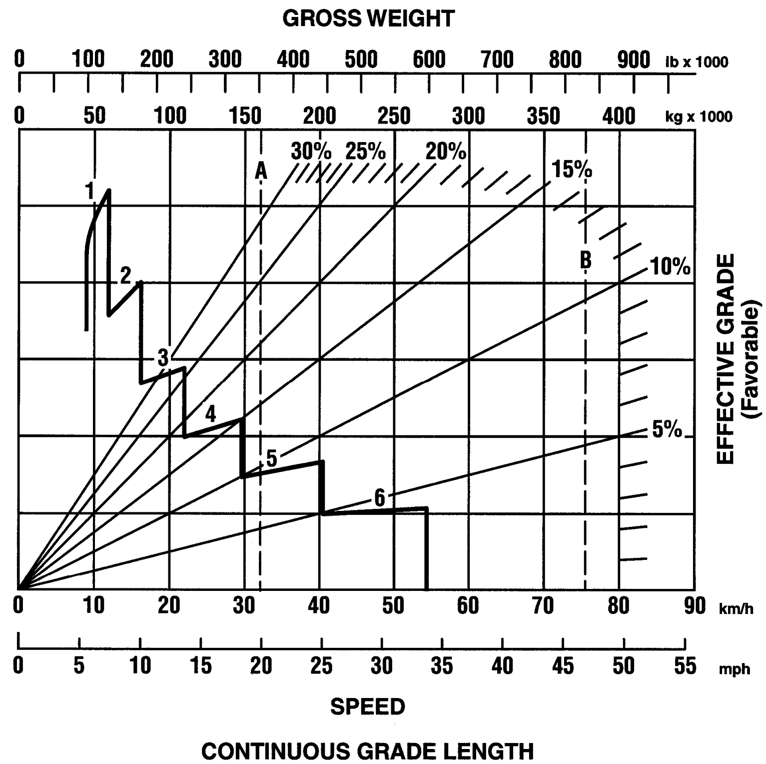



Figure 8-3 793C brake performance, A- estimated field empty weight 158760kg, B- max. GVW 376488kg (Caterpillar 1999).

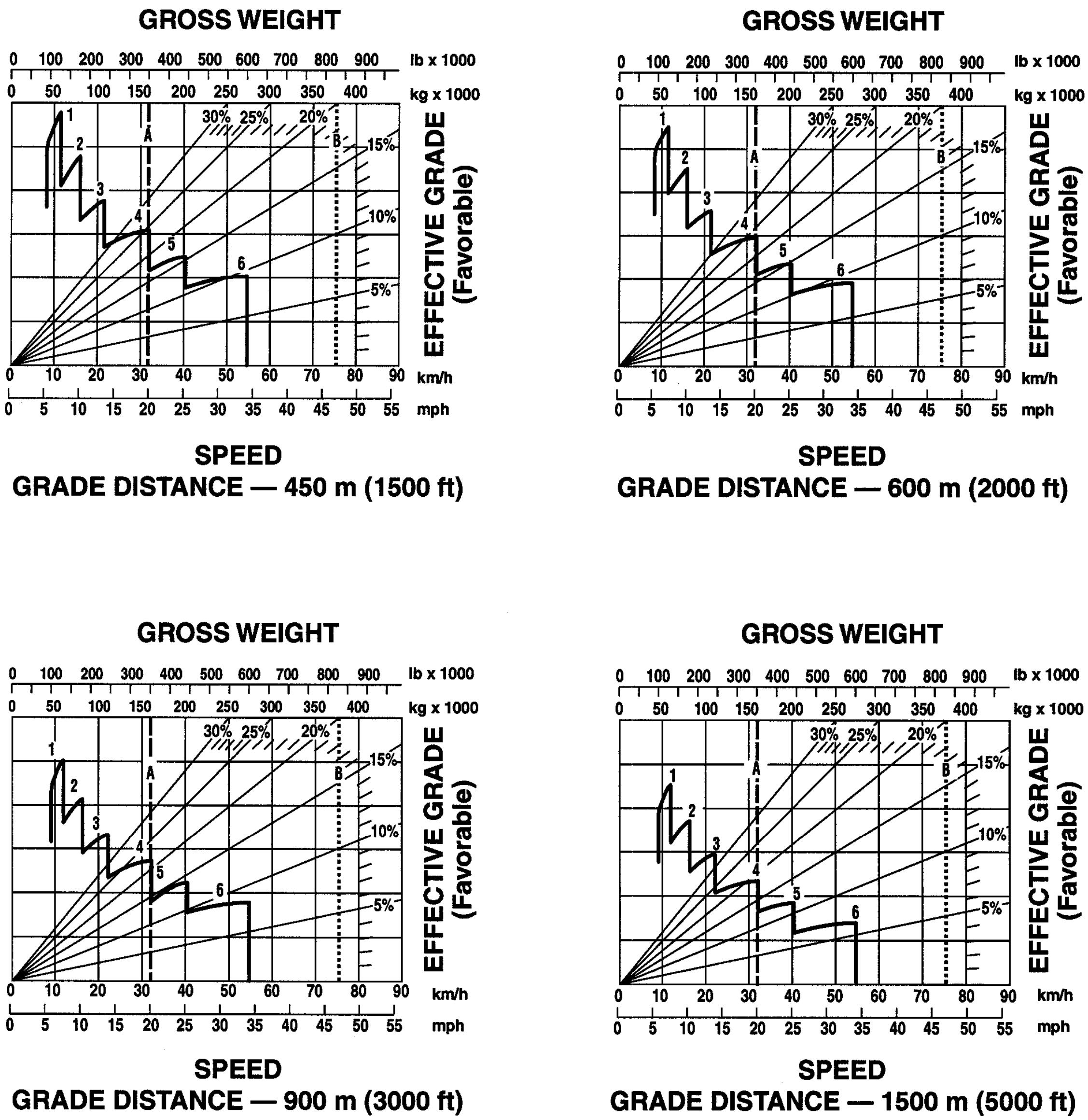



Figure 8-4 793C brake performance, A- estimated field empty weight 158760kg, B- max. GVW 376488kg (Caterpillar 1999).

## 8.4 Truck Tires

Haul truck tires have grown with the size and capacity of trucks, thus becoming a very costly piece of equipment. A single tire can cost up to $39,000 and can account for 20% to 25% of a haul truck's operating costs in an open pit mine (Werniuk 2000). Given the constraints due to the tires on the size of haul trucks and the high cost of tires, it is important to understand the construction of tires and factors that affect their performance.

The major component materials of a tire are: rubber (both synthetic and natural), carbon black, sulphur, steel cord and bead wire, polyester and nylon, and other chemical agents. A common ratio of rubber to other materials is 50:50 for a radial car tire and about 80:20 for an off-road haul truck tire. For large haul truck tires, about 80% of the rubber comes from natural sources. A higher proportion of natural rubber means a greater capacity to dissipate heat, but lower wear resistance. A higher proportion of carbon black leads to greater wear resistance of tires, but carbon tends to retain heat, thus the tire gets heated more easily. As such, the selection of proper composition depends on the nature of the application. If the haul road has an abrasive surface, a tire with a greater percentage of carbon black would be desired. But, if the haul road is smooth and free of abrasive materials, a tire with higher percentage of natural rubber would give better service in terms of tonnes kilometre per hour (tonne-km/hr).

There are two major types of tire: bias ply and radial. Bias ply tires (Figure 8-5) use nylon casing plies to form the carcass, and have several bead bundles. Radial tires generally use a steel carcass ply radially about the tire. The bead may typically be formed by only one bundle of wires. Compared to bias ply tires, radial tires have longer tread life, greater stability, more uniform ground pressure, and lower rolling resistance. For these reasons, large haul trucks tend to use radial tires (see Table 8-3). 95% of the tires used on large surface haul trucks are radial tires (Werniuk 2000). Although more expensive, the radial tires deliver lower costs by giving two to three times the tire life, increased fuel efficiency, more protection from flats and cuts, and better traction compared to bias ply tires.

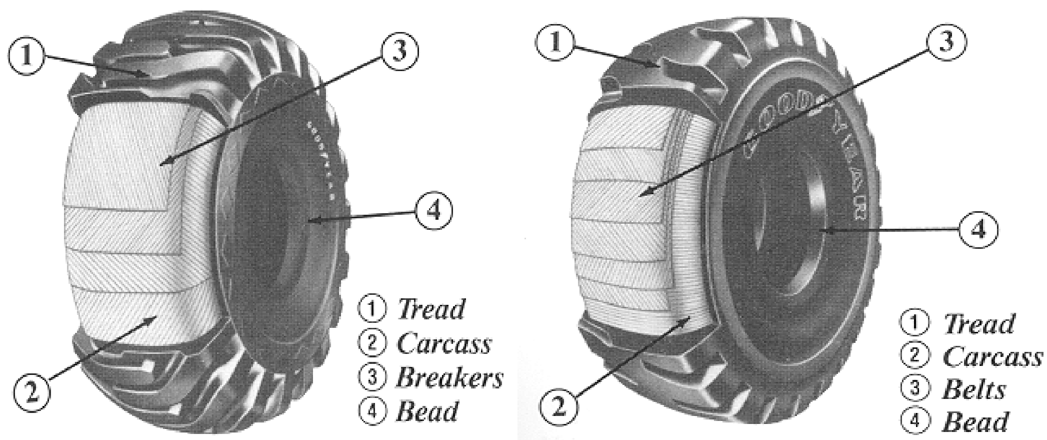



Figure 8-5 Bias ply and radial tires (Good Year 1998).

The components of a typical tire are described in detail in the *Tire Maintenance Manual* by Good Year (1998) (Figure 8-5). Another good source of information on tires is the *Caterpillar Performance Handbook* (1999). Tread is the outermost part of the tire, which is in contact with the ground, thus providing traction. It should have cut and wear resistance required by the site and application needs. Greater wear and cut resistance is obtained by using tires with deeper tread designs. However, as the tread depth increases, the tire's ability to dissipate heat reduces and the tonne-km/hr rating drops. A road design that minimizes the presence of loose rocks and has a smooth running surface permits the use of tires with higher tonne-km/hr ratings.

The strength of the carcass determines the extent of inflation pressure that a tire can withstand. Breakers (or belts) are placed between the tread and the carcass. Their function is to distribute road shock to protect the carcass. They also control the tire diameter, and give it better impact and penetration resistance. The bead is bundles of high tensile steel wire, which anchors the tires to the rim. Sidewalls are the protective rubber cover of the carcass on the sides of a tire.

Two important elements of tires that affect haul road design are foot print area and tire pressure. Tire pressure has gone up to 690kPa (100psi) from 551kPa (80psi) during last five years.

Although the new low profile truck tires (55/80R63) have an inflation pressure of 600kPa (87 psi) (Table 8-4). The increase in tire pressure has placed greater stresses on the road surface. The bearing capacity of materials used for the surface layer should be greater than the tire pressure. So, any material having a bearing capacity less than roughly 1MPa (equivalent to compressive strength of soft rock) cannot be used for the surface layer. Due to the large tire foot print areas, the stress bulb below a tire can extend quite deep resulting in the need for well-designed sub-base and base layers with sufficient bearing capacities and stiffness. The shape of tire footprint can be approximated as a rounded rectangle. The footprint is longer for low profile, low-pressure tires or for tires operating below their recommended inflation pressure. The pressure distribution beneath a tire is non-uniform, especially for bias ply tires. However, an assumption of uniform pressure distribution across the tire foot print area for the purpose of stress analysis in haul road layers gives reasonably satisfactory results.

Table 8-4 Michelin radial tire specifications (Doyle 1999).

| Tire | Truck payload | Footprint area ($m^2$) | Load per tire | Tire pressure kPa (psi) | Free radius (mm) |
|---|---|---|---|---|---|
| Standard tire 40.00R57 | 218mt | 1.11 | 63mt | 689 (100) | 1776 |
| Retrofit tire 44/80R57 | 218mt | 1.13 | 63mt | 586 (85) | 1705 |
| Low profile 55/80R63 | 327mt | 1.68 | 93mt | 586 (85) | 1946 |

Tire selection and machine operating practices have important consequences on haulage costs. One of the most serious problems occurs when tires are operated at temperatures above their capabilities. Separation and related tire failures can occur.

Tire manufacturing requires heat in the vulcanizing process to convert crude rubber and additives into a homogeneous compound. The heat required is typically above 132°C. A tire also generates heat as it rolls and flexes. Heat generated faster than it can be radiated into the atmosphere gradually builds within the tire and reaches maximum level at the outermost ply or belt. Over time, enough heat can develop from over-flexing to actually reverse the vulcanizing process or “revert” the rubber causing ply separation and tire failure. Only a brief time at reversion temperature initiates the failure. Experience shows that few pure heat separation cases occur. Most so-called heat separations occur in tires operating below the reversion level. As a tire operating temperature increases, the rubber and textiles within the tire significantly lose strength. This allows the tire to become more susceptible to failures from cornering, braking, impact, cut through, fatigue, and heat separation.

The tonne-kilometre per hour (tonne-km/hr) rating of a tire indicates the working capacity of the tire and was developed to predict tire temperature buildup. The system is a method of rating tires in proportion to the amount of work they can do from a temperature standpoint. It uses the product of *load x speed* to derive an index for the maximum allowable internal temperature of a tire (Tully 1997). Maximum tire level-off temperatures of 107°C for fabric cord tires and 93°C for steel wire tires are the limits that Caterpillar recommends. Even at these temperatures, failures may be initiated by over stressing the tires.

Heat generation in a specific tire at recommended pressure depends on three factors: the weight the tire is carrying (flex per revolution), the speed the tire is travelling over the ground (flexures over a period of time), and the air temperature surrounding the tire (ambient temperature) and road surface temperature. Once a tire manufacturer has determined a tire’s temperature characteristics and expressed them in tonne-km/hr, the specific job conditions can be used to determine any tire’s maximum work capacity and to predict and avoid costly tire separations.

Tonne-km/hr for an operation can be calculated as follows:
Tonne-km/hr = Qm x Vm x K1 x K2
Where: Qm = mean load on a tire over the cycle of operation (tonnes)
Vm = average speed for a haul cycle (km per hour)
K1 = correction for length of haul cycles (K1 = 1 for 5km and increases to 1.2 at 25km)
K2 = correction for temperature of operation (K2 = 1 at 38°C decreases for cooler temperatures and increases for warmer temperatures).

For example: If a truck travels at an average speed of 45km/hr and the mean load over a tire is 60mt (assuming a length of cycle of 5km and working at ambient temperature of 38°C), then the tonne-km/hr of the tires should be more than 45 x 60 or 2700, as the tire selected should have greater tonne-km/hr rating than the tonne-km/hr calculated above. But, if we look at the tonne-km/hr rating chart of some larger Bridgestone tires (Table 8-5), the largest tonne-km/hr value is only 1117. Thus, these tires would not be appropriate.

Table 8-5 tonne-km/hr rating at 38°C – radial tires (Tully 1997).

| TRA Classification | | | | | | | |
|---|---|---|---|---|---|---|---|
| Pattern | | E4 VRLS | | | E4 VELS | | |
| Bridgestone Code No. | | 2A | 1A | 3A | 2A | 1A | 3A |
| Tire Size | 37.00R57 | 694 | 858 | 953 | | | |
| | 40.00R57 | | | | 773 | 955 | 1117 |

Tonne-km/hr ratings for various tires made by Goodyear, Michelin and Bridgestone are listed in the *Caterpillar Performance Handbook* (1999). Michelin has reported specifications for some of its tires used for large trucks (Doyle 1999), which are summarized in Table 8-4. Footprint area, load per tire and tire pressure determine the nature of stress distribution in the soil beneath the tire, hence are important characteristics of the tire.

The factors affecting tire life include: road conditions (curves, grades, superelevation, haul length, road surface and maintenance), operating conditions (average speed, speed in curves), truck conditions (weight distribution, struts, air pressure in tires, tire matching, tread depth, and tire type), and weather (temperature and precipitation). Table 8-6 shows typical values for tire life reduction caused by inflation pressure and various road conditions. Tire inflation pressure should be monitored regularly because it can significantly affect tire life. Travelling at a speed that is compatible with the curve radius and superelevation can minimize tire damage occurring on curves.

Table 8-6 Factors affecting average tire life (TLR = tire life reduction).

| Inflation Pressure | TLR | Road Conditions | TLR |
|---|---|---|---|
| Recommended press. | 0% | Average soil, no rock | 0% |
| 10% under | -10% | Ave. soil, scattered rock | -10% |
| 20% under | -25% | Well maintained with smooth gravel | -10% |
| 30% under | -70% | Poorly maintained with ungraded gravel | -30% or more |
| 20% over | -10% | Scattered blast rock | -40% or more |
| **Curves** | **TLR** | **Grade** | **TLR** |
| None | 0% | None | 0% |
| Smooth | -10% | <6% | -10% |
| Sharp | -20% or more | <15% | -30% |

Tire tracking at three hard rock mines showed that the tire life for 40.00R57 tires varied from 1500 to over 10,000 hours. The typical tire life was about 6500 hours. A similar study on 40.00R57 tires used in two different oil sands mines showed a similar trend in the data but with slightly longer tire life occurring in the oil sands mines. In both mining environments, the tire life can range over an order of magnitude.

# 9 BEARING CAPACITY AND VERTICAL STRAIN

## 9.1 Introduction

For the surface layer, the pressure bulbs caused by individual tires can be assumed to be non-interfering and stress analysis for the surface layer can be done using a single tire. In contrast, at depths below the road surface about 0.5m, the stress bulbs from individual tires on rear axles begin to interact and the magnitude of vertical stresses in the road also depends on the tire spacing on the truck.

For designing any haul road, it is imperative to understand the stress and strain distribution in the haul road cross-section induced by the haul truck tires. Theoretical analysis of stress with respect to the bearing capacity of the soil was done to show that the vertical strain, not the bearing capacity, is the limiting factor in most haul road designs. The vertical strain distribution was analyzed using Phase$^2$ software, which is a two-dimensional finite element program for calculating stresses and displacements. The objective of the modelling is to analyze vertical strain distributions for various combinations material rigidity and different thickness of haul road layers. As discussed in section 3.3, the haul road cross-section is adequate if the stress at any point is less than the bearing capacity of the material and the vertical strain is less than the critical strain limit (generally assumed between 1500 to 2000 micro-strains). The adequacy of the haul road cross-section for the given wheel load(s) is examined using these stress and strain criteria for various models discussed.

Different cases listed in Figure 9-1 were analyzed. The load distribution on the road surface beneath a tire was assumed uniform over a circular area for all analyses. Bearing capacity analysis (case A of Figure 9-1) was done using a circular footing to represent a tire. Phase$^2$ was used for case B, C and D analyses. An axisymmetric model was used to analyze the effect of different combinations of layer moduli (case B of Figure 9-1) on strain bulbs below a single tire. Various combinations of moduli were analyzed including uniform moduli (B1), surface layer stiffest (B2), base layer stiffest (B3), and sub-base stiffest (B4). The combination that gave the best result (least strain), namely case B2, was used to study the effect of layer thickness on the strain bulbs (case C). The thinnest layer, which satisfied the critical strain limit, namely case C3, was used to study the effect of interaction of vertical strain bulbs generated by a set of two and four tires along the back axle of a truck (Case D).

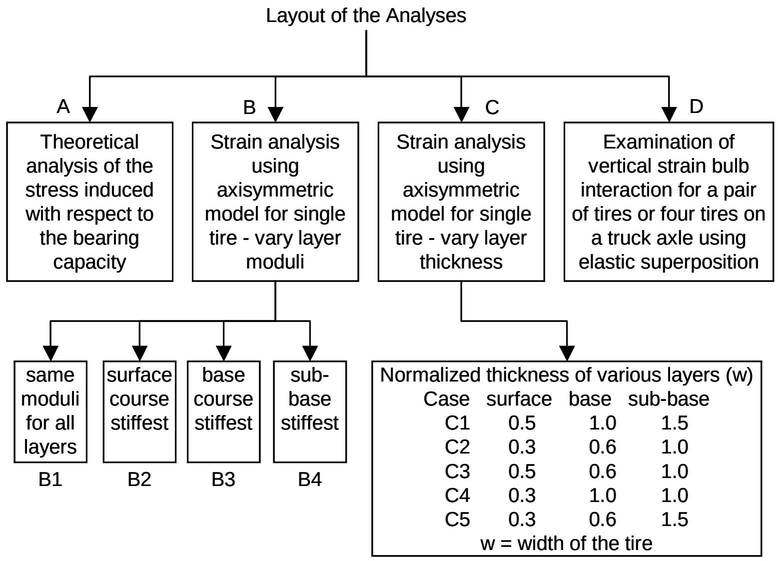



Figure 9-1 Layout of the models.

## 9.2 Bearing Capacity Analysis

Bearing capacity of a soil depends on its shear strength, which in turn depends on the soil's cohesion c and angle of friction $\phi$. Most of the bearing capacity theories are based on the plasticity theory. Prandtl developed the following expression for ultimate bearing capacity $q_{ult}$ for footings by assuming failure conditions shown in the Figure 9-2 and undrained ($\phi = 0$) conditions (Bowles 1984).

$$q_{ult} = (\pi + 2)c = 5.14c$$

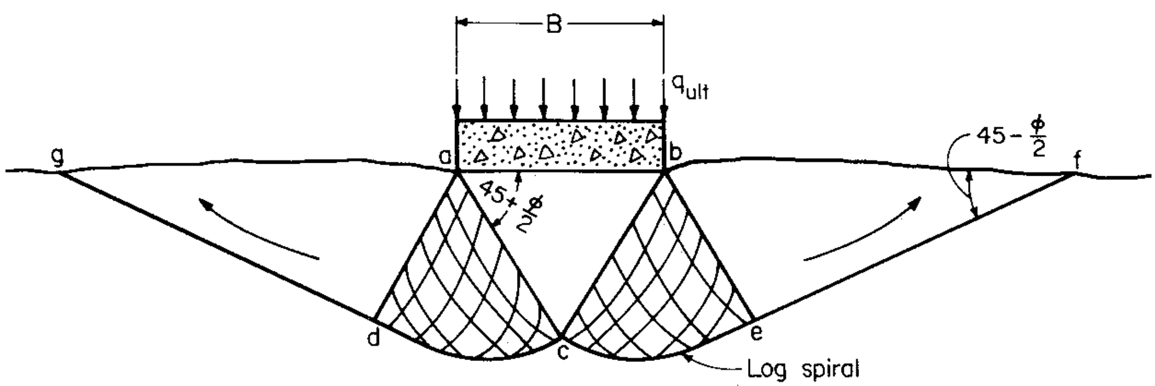



Figure 9-2 Bearing capacity failure under a surface footing or tire (after Bowles 1984).

Terzaghi (1943) modified the expression for circular footings as follows:

$$q_{ult} = 1.3cN_c + \gamma DN_q + 0.6\gamma RN_\gamma$$

Where: D = footing depth (m)
R = footing radius (m)
$\gamma$ = unit weight of the soil ($kN/m^3$)
$N_i$ = bearing capacity factors ($\phi$ dependent) as shown in Figure 9-3

The load exerted by a tire can be approximated by a circular footing. For a tire, the footing depth D is zero and footing radius is equal to half of the tire width.

Apart from footing (tire) geometry and unit weight of soil, the bearing capacity of a soil depends on the cohesion and the angle friction of the soil. Figure 9-4 shows a plot of normalized bearing capacity versus angle of friction and cohesion. The ultimate bearing capacity was calculated using Terzaghi's equation, using R = 0.7m (for tire 55/80R63), $\gamma = 20kN/m^3$ and reading $N_i$ from Figure 9-3 for various values of $\phi$. The dashed line in Figure 9-3 is for undrained conditions but haul road construction materials are mostly granular so solid lines representing drained conditions were used for reading $N_i$ values. The factor of safety was calculated by dividing the ultimate bearing capacity by the applied stress, which was assumed equal to the tire pressure (700kPa). Bowles (1984) recommends using 2.0 as factor of safety for cohesionless soil and 3.0 for cohesive soils for footings. The materials used for road construction are mostly cohesionless (or low cohesion), especially for the surface layer. Moreover, some local failure (rutting) is allowable for haul roads, which is not the case for footings. So, a factor of safety of 2.0 can be taken as safe. The surface layer of a haul road is generally built with compacted gravel. The cohesion of compacted gravel can be assumed zero and the angle of friction ranges between 35° and 50° depending on the degree compaction and gravel characteristics. For well-compacted good quality gravel, $\phi$ can be taken as 45°, thus from Figure 9-4, the factor of safety is about 6. Thus, bearing capacity should not be a concern in most haul road designs. It is the vertical strain or the settlement, which is the limiting factor.

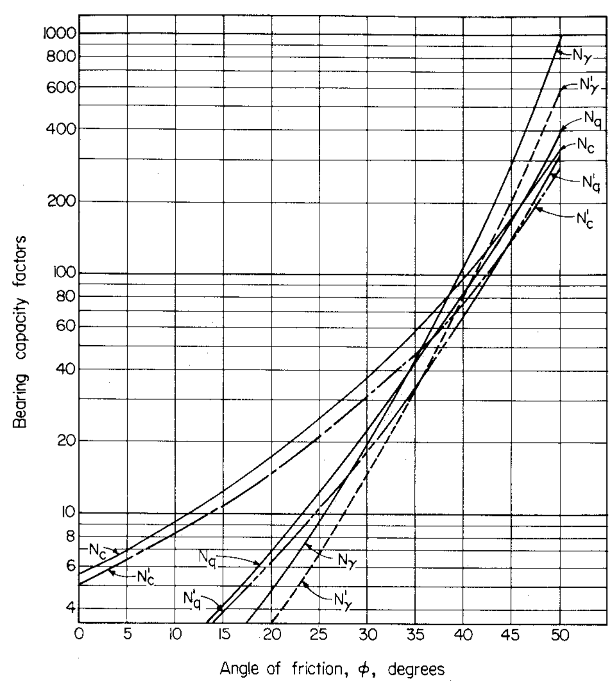



Figure 9-3 Bearing capacity factors for Terzaghi equations (after Bowles 1984).

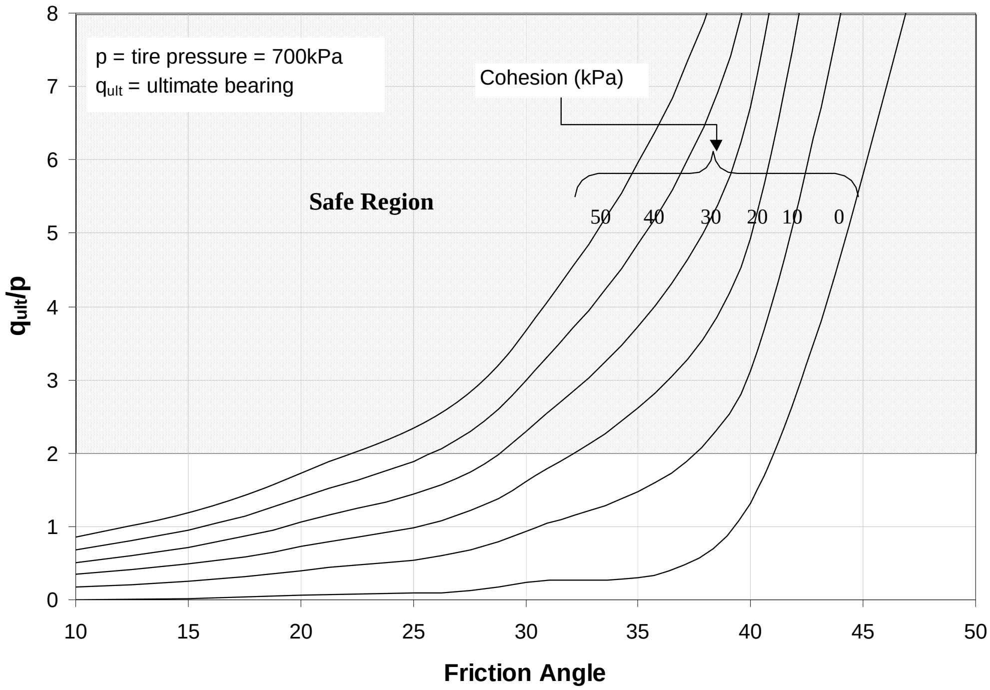



Figure 9-4 Factor of safety ($q_{ult}/p$) versus friction angle and cohesion.

Table 9-1 Bearing capacity of various materials (Monenco 1989).

| Material | Bearing capacity (kPa) |
|---|---|
| Hard, sound rock | 5500+ |
| Medium hard rock | 2750 – 4150 |
| Hardpan overlying rock | 900 – 1240 |
| Dense gravel, very dense sand and gravel | 830 – 1100 |
| Soft rock | 700 – 830 |
| Medium dense to dense sand and gravel | 550 – 700 |
| Hard dry over consolidated clay | 410 – 550 |
| Loose, coarse to medium sand, medium dense fine sand | 205 – 410 |
| Compact sand - clay soils | 205 – 275 |
| Loose fine sand, medium dense sand – silt soils | 100 – 205 |
| Firm or stiff clay | 70 – 140 |
| Loose saturated sand, medium soft clay | 35 – 70 |
| Muskeg, peats, marsh soils | 0 – 35 |
| Loose to medium dense mine spoil | 35 – 520 |

## 9.3 Finite Element Strain Analyses

Finite element strain analyses were done using Phase$^2$, a two-dimensional finite element program for calculating stresses and displacements. Phase$^2$ can be used to solve a wide range of mining and civil engineering problems (RocScience 2000). The program can be used for elastic analyses, but also supports plasticity. Although the software is primarily designed for underground problems, it can be used to solve two-dimensional near-surface problems including those involving traction (or surface loads) such as wheel loads.

The axisymmetric option was selected as it allows a circular load, whereas the plane strain option simulates a strip load (of infinite length) A circular stress distribution on the road surface is better approximation of a tire than a strip load.

The assumptions used to generate the models are:

- Type of model used – axisymmetric
- Size of half model = 15w (width) x 7w (depth), where w is the width of tire footprint
- Type of material = isotropic and elastic
- Mesh type – graded
- Element type – 4-noded quadrilaterals
- Number of elements = 1600
- Number of nodes = 1700
- Poisson's ratio = 0.4
- Loading = 1MPa stress over a circular area (diameter w)

Since the applied stress is 1MPa, the stresses or strains calculated by the model can be scaled by the actual stress exerted by the tire on the road (generally taken as the tire pressure). Given that 700kPa is a common tire pressure for haul trucks, the model output (stress or strain) shown in subsequent figures has been obtained by multiplying the model output by 0.7. Moreover, the model dimensions can also be scaled by the actual tire size. For example, the depth is shown in multiples of tire width (w). Figure 9-5 shows a typical axisymmetric model used to generate vertical strain plots in the subsequent sections. The axis of rotation is at x = 0 (x and y are horizontal and vertical axes, respectively). The wheel load is applied between the points (0,0) and (0,0.5). The boundary of the model (at y = 0) represents the surface of the haul road and thus is a free boundary. The vertical boundaries of the model (at x = 0 and x = 15) are restrained in x direction, thus the material at the boundary is allowed to move in vertical (y) direction only. The lower boundary of the model (at y = -7) is restrained in y direction. The right and lower boundaries are chosen to be at a reasonable distance from the tire, so that the boundary conditions do not affect the stresses and strains beneath the tire. The top layer (between y = 0 and y = -0.5) represents the surface layer. While the base layer is between y = -0.5 and y = -1.5, the sub-base is between y = -1.5 and y = -3.0. The layer below y = -3.0 represents the sub-grade or insitu material. The thickness, thus the boundaries of different layers vary for models in section 9.5, in order to analyze the effect of varying thickness on strain bulbs.

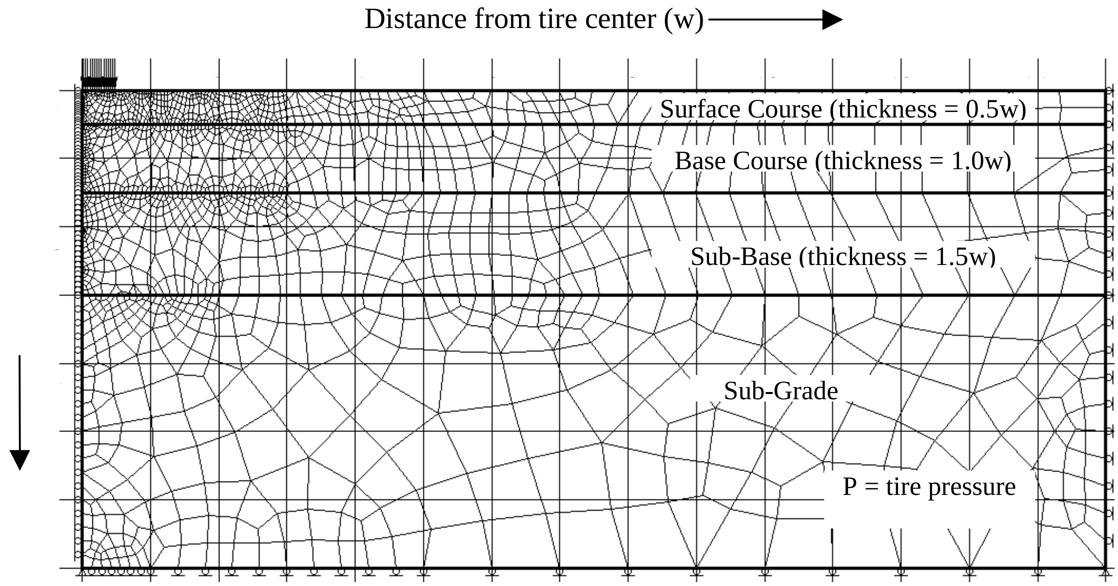



Figure 9-5 Axisymmetric model for case B study.

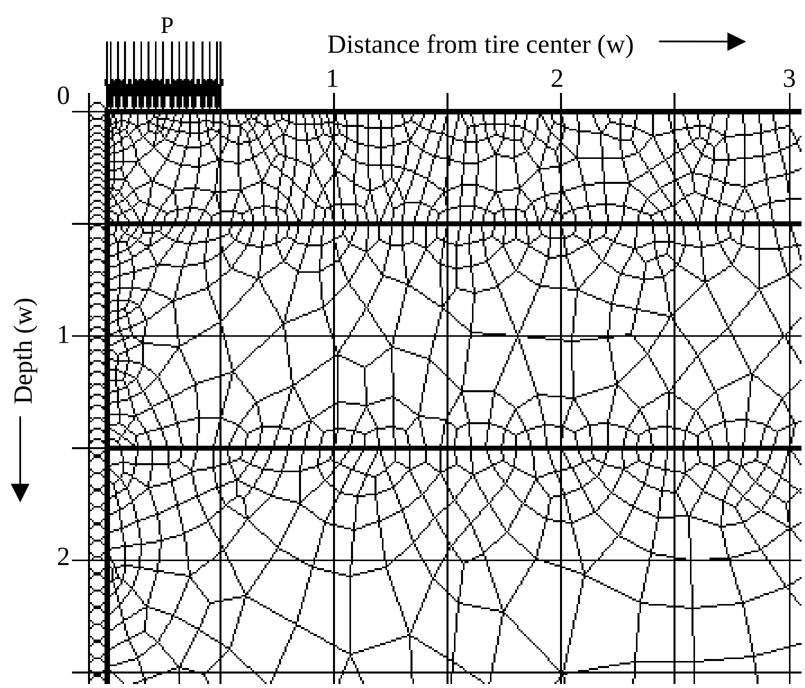



Figure 9-6 Meshing near the tire (zoomed view of Figure 9-5).

An axisymmetric model allows only one circular load (or tire) in a model. So, the effect of strain bulb interaction cannot be studied directly in a Phase$^2$ model. However, the principle of elastic superposition allows superposition of elastic stresses or strains. Therefore, the axisymmetric model was used to generate the vertical strain distribution below a single circular tire load and the results were numerically superimposed to simulate strains beneath two to four tires of the back axle of a loaded truck. The result thus obtained was then contoured.

## 9.4 Effect of Layer Stiffness on Vertical Strain

The axisymmetrical Phase2 model was generated to analyze vertical strain below a circular load for different combination of materials, including uniform stiffness across the layers, stiff surface layer, stiff base layer and stiff sub-base. The thickness of various layers for the analyses was:

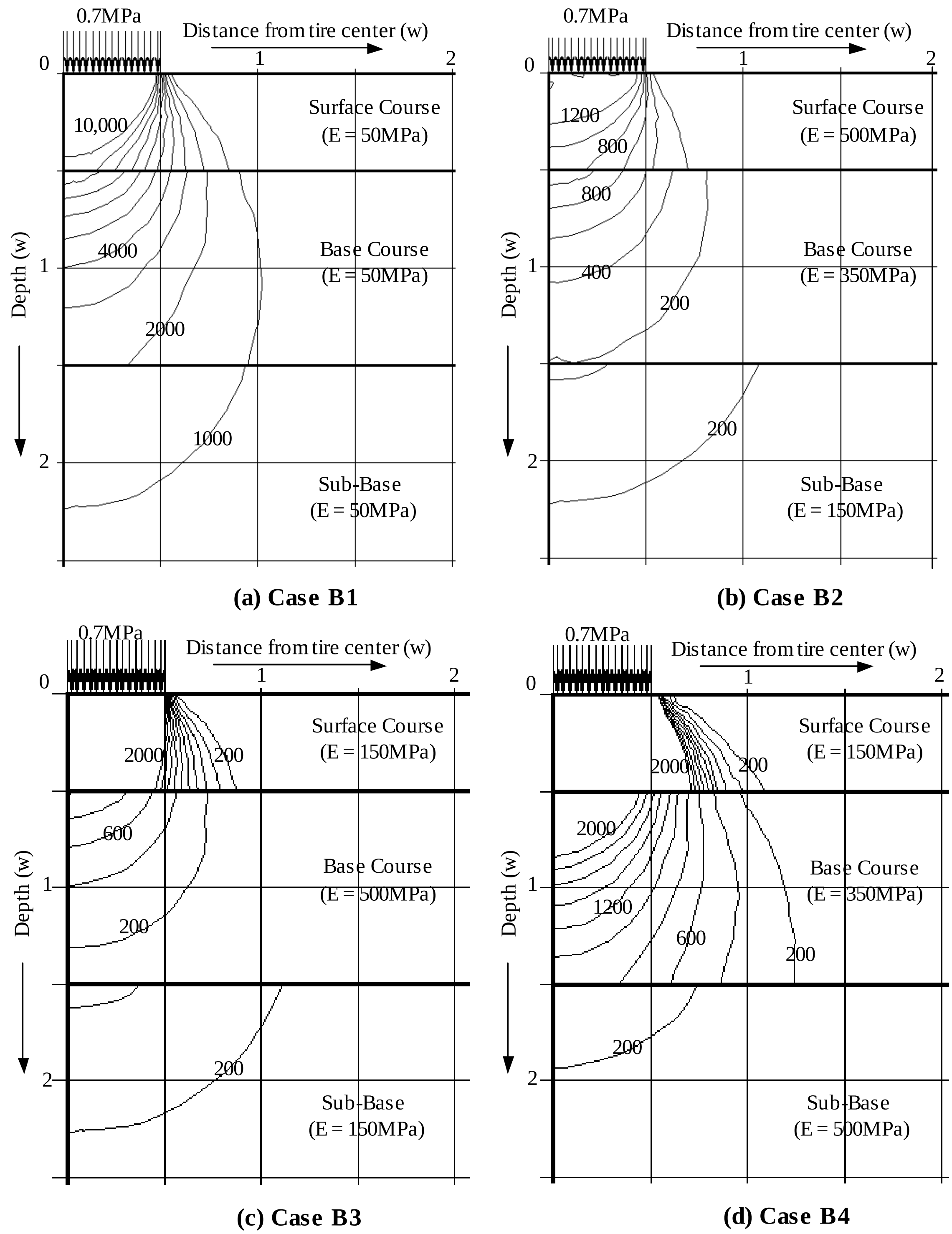
- Surface = 0.5w
- Base = 1.0w
- Sub-base = 1.5w

Table 9-2 shows the Young's modulus assigned to various layers for the different cases studied in this section.

Table 9-2 Young's modulus (MPa) of various materials for different cases.

| Layer | Uniform material (B1) | Stiff surface (B2) | Stiff base (B3) | Stiff sub-base (B4) |
|---|---|---|---|---|
| Surface | 50 | 500 | 350 | 150 |
| Base | 50 | 350 | 500 | 350 |
| Sub-base | 50 | 150 | 150 | 500 |
| Sub-grade | 50 | 50 | 50 | 50 |

Figure 9-7 shows the effect of layer moduli on the strain bulbs below a tire. The shift in contours at the boundary of different layers (more evident in cases B2 through B4) is due to the difference in the layer moduli. In case B1 the contours should have been smooth through the boundaries of adjacent layers and the shift in the contours is the artifact of the model (due to meshing at the boundary). The stress level in the haul road cross-section decreases with depth. Thus if the Young's modulus is same for all layers then the strain will be highest at the top layer and decreases with the depth. Thus, Case B1 gives extremely high vertical strain for surface layer. Also, cases B3 and B4 result in very high strain in the surface layer (more than 2000 micro-strain, which is unacceptable) because the stiffest material is not used for the surface layer. Case B2 has material with highest Young's modulus as surface layer and stiffness of each layer decreases with the depth. This moduli distribution results in the lowest vertical strain, which at all point is less than the critical strain limits (1500-2000 micro-strains). Therefore, it can be concluded that a haul road should have the stiffest material at the top and the stiffness of various layers should decrease with depth. Fly ash can be added to haul road construction materials to increase their stiffness. The greatest benefit comes from having the stiffest layer near the road surface. This means placing fly ash stabilized materials in the base layer. Since the use of fly ash in the running surface is not recommended. Case B2 will used to study the effect of layer thickness on the vertical strain bulbs.




Numbers on contour are strains in micro-strain

Figure 9-7 Vertical strain bulbs for different combinations of Young’s moduli.

## 9.5 Effect of Layer Thickness on Vertical Strain

The axisymmetrical model similar to that used in section 9.3 was used to study the effect of varying layer thickness on strain bulbs. The thickness of the layers is given in Table 9-3.

Table 9-3 Thickness of layers for different cases (normalized to tire width).

| Layer | Case number | | | | |
|---|---|---|---|---|---|
| | C1 | C2 | C3 | C4 | C5 |
| Surface | 0.5 | 0.3 | 0.5 | 0.3 | 0.3 |
| Base | 1.0 | 0.6 | 0.6 | 1.0 | 0.6 |
| Sub-base | 1.5 | 1.0 | 1.0 | 1.0 | 1.5 |

Case C1 is the same as case B2 of Figure 9-7. Vertical strain bulbs for cases C2 through C5 are shown in Figure 9-8. As evident from the figure, the vertical strain in a layer increases as the cover thickness (total thickness of layers above) decreases. Thus, the base layer in case C2 (0.3w cover thickness) has the highest strain (1400 micro-strain), whereas the base layer in case C3 (0.5w cover thickness) has a maximum vertical strain of 1000 micro-strain. The cost of road construction increases with increase in the cover thickness (because more construction material is used per kilometre of road). So, the case that has least cover thickness should be selected, provided that the maximum strain in any layer is below the critical strain limit (generally assumed to be between 1500-2000 micro-strains) with some allowance for the fact that these strain bulbs are due to only one tire and interaction of the tires would increase the strain levels in each layer. So, case C3 can be safely selected for analyzing effect of tire interaction, as the vertical strain at any point is less than 1200 micro-strains.

From the above discussion, it is evident that required thickness of various layers is primarily dependent on the load configuration and the material stiffness. For the tire pressures and material properties assumed, a 0.6m surface layer, 0.75m base layer and 1.25m surface layer would be adequate, assuming a critical strain limit of 1500 micro-strain.

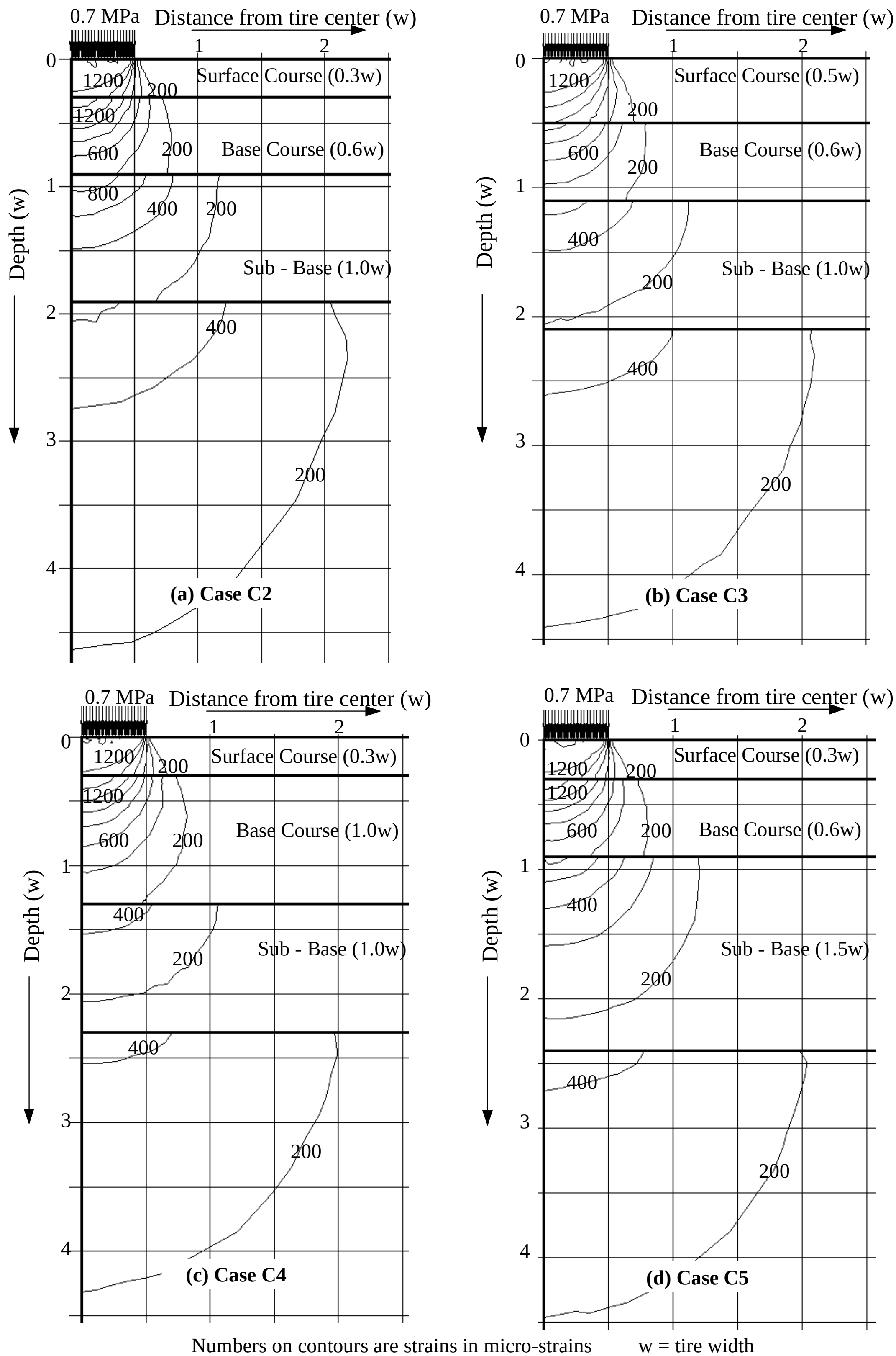



Figure 9-8 Vertical strain bulbs for different layer thickness.

## 9.6 Effect of Tire Interaction

As stated earlier, the axisymmetric model of Phase[2] allows only one circular load (tire), but in reality, the strain bulbs generated by different tires along a truck axle interact and the resultant vertical strain generated is greater than that by one tire. The effect of tire interaction was examined by superimposing the strain bulbs generated by one tire to represent multiple tires of a truck. The most critical case is the back axle of the truck, which has four tires, whereas the front one has only two. Moreover there is little interaction between front and back tires of a truck, as the vertical strain generated is insignificant at a horizontal distance of 2.5w from the tire centre and the distance between the centres of the front and rear axles is 5.3w (Komatsu 930E), w being the width of the tire (≈ 1.2m).

Case C3 (section 9.5) was used to generate strain bulbs for one tire. Data was queried at a grid of 0.05w x 0.05w for horizontal distance of 2.5w and vertical distance of 0.7w. The data was mirrored to generate full strain bulbs for one tire, as an axisymmetrical model generates only half of the space. Then the strain values at grid points were staggered by a horizontal distance of 1.15w and added to generate strain values at various grid points to represent vertical strain generated by two adjacent tires (Figure 9-9). The result obtained by the above procedure was staggered again by a horizontal distance of 4.1w to get values of vertical strain at grid points representing strains generated by four tires along the back axle of a truck.

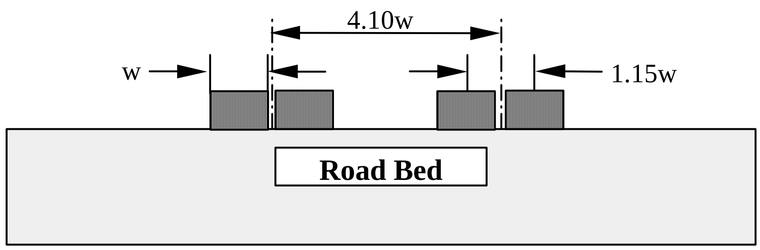



Figure 9-9 Schematic diagram for position of tires on back axle of a Komatsu 930E.

The data thus generated for the three cases (one tire, two tires and four tires) were plotted using WINSURF software, which is a grid-based contouring program. Linear krigging was used as the gridding method. The data were then contoured using a 200 micro-strain contour interval. The result thus obtained for each case is shown in Figure 9-10 through Figure 9-12. The approximate maximum vertical strains estimated from the figures for the various layers are summarized in Table 9-4.

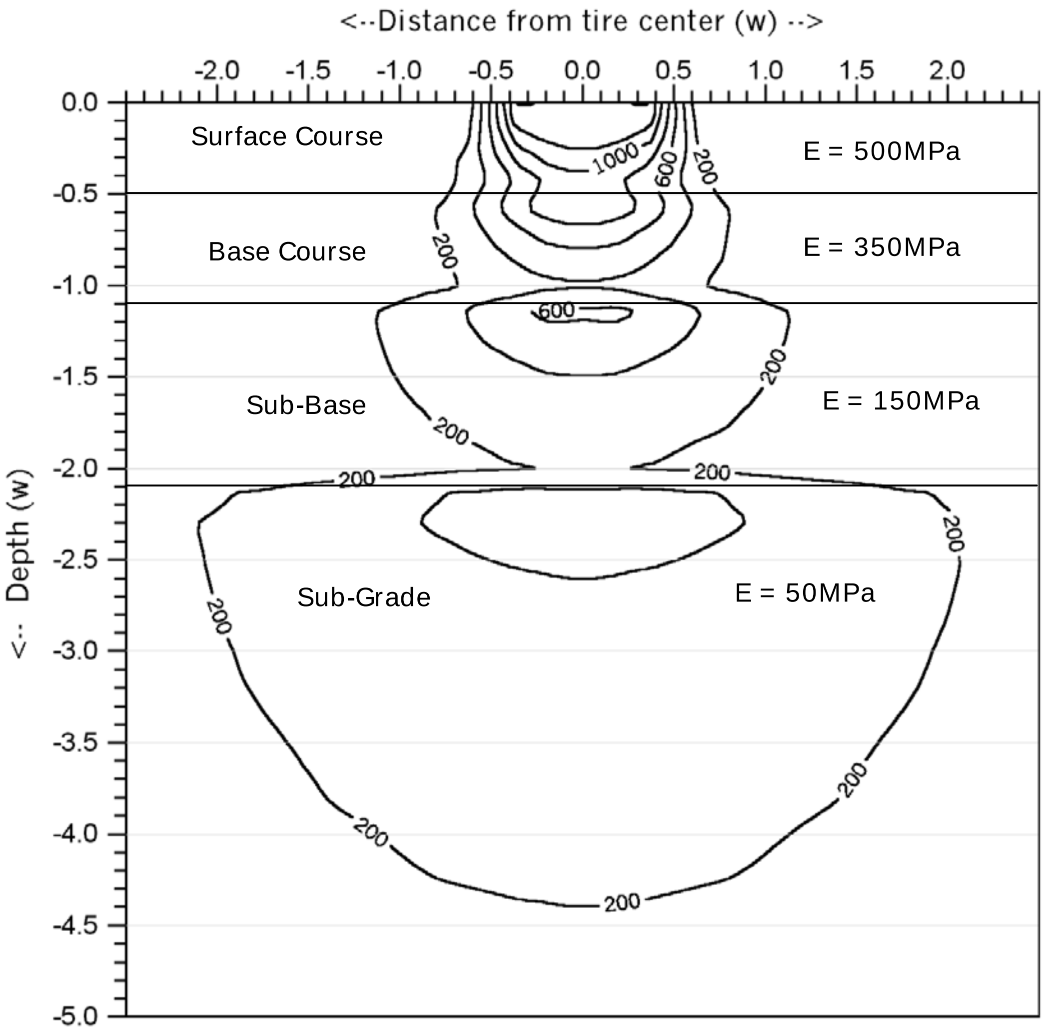



Figure 9-10 Vertical strain (in micro-strain) for one tire (pressure = 0.7MPa).

Table 9-4 Maximum vertical strain for various layers.

| Layer | One tire | Two tires | Four tires |
|---|---|---|---|
| Surface | 1400 | 1400 | 1400 |
| Base | 900 | 1100 | 1100 |
| Sub-base | 700 | 900 | 900 |
| Sub-grade | 500 | 900 | 900 |

Study of the figures and the table reveals that interaction between adjacent tires affects the vertical strain levels in the base layer and below. The effect of tire interaction is not significant in surface layer because the strain bulbs in that layer are not wide enough to interact. In the base layer, the maximum strain level increased from 900 to 1100 micro-strain, when more than one tire was considered. The increases for sub-base and sub-grade were from 700 to 900 micro-strains and from 500 to 900 micro-strains respectively. The interaction between the pairs of tires at the opposite end of the rear axle of the truck does not affect the maximum strain level in any layer, but the strain bulbs extends deeper in the sub-grade (400 and 600 micro-strain contours).

Thus it can be concluded that interaction of strain bulbs generated by the tires along the back axle of a truck significantly increases the vertical strain level in the base layer and below.

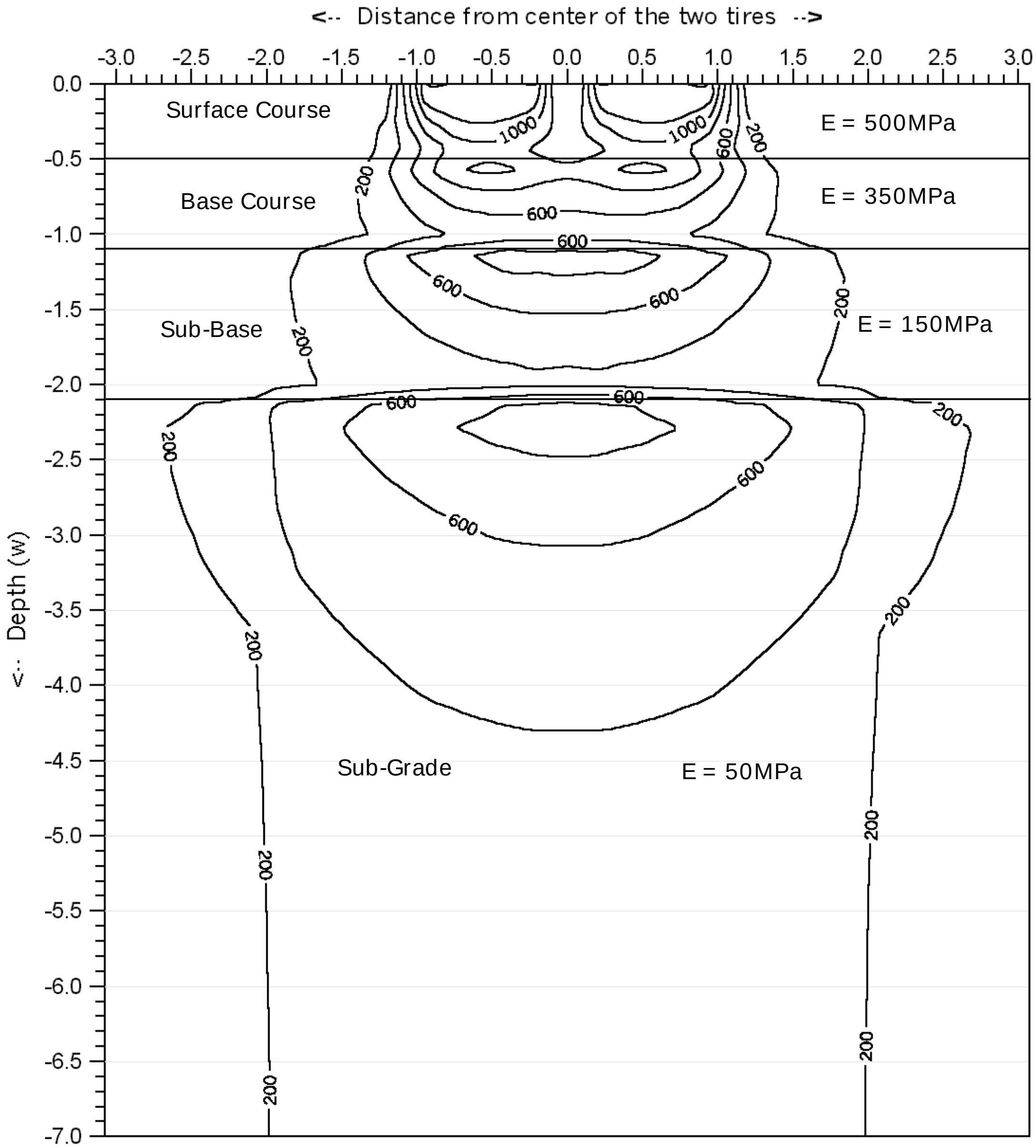



Figure 9-11 Vertical strain (in micro-strain) for two tires (pressure = 0.7MPa).

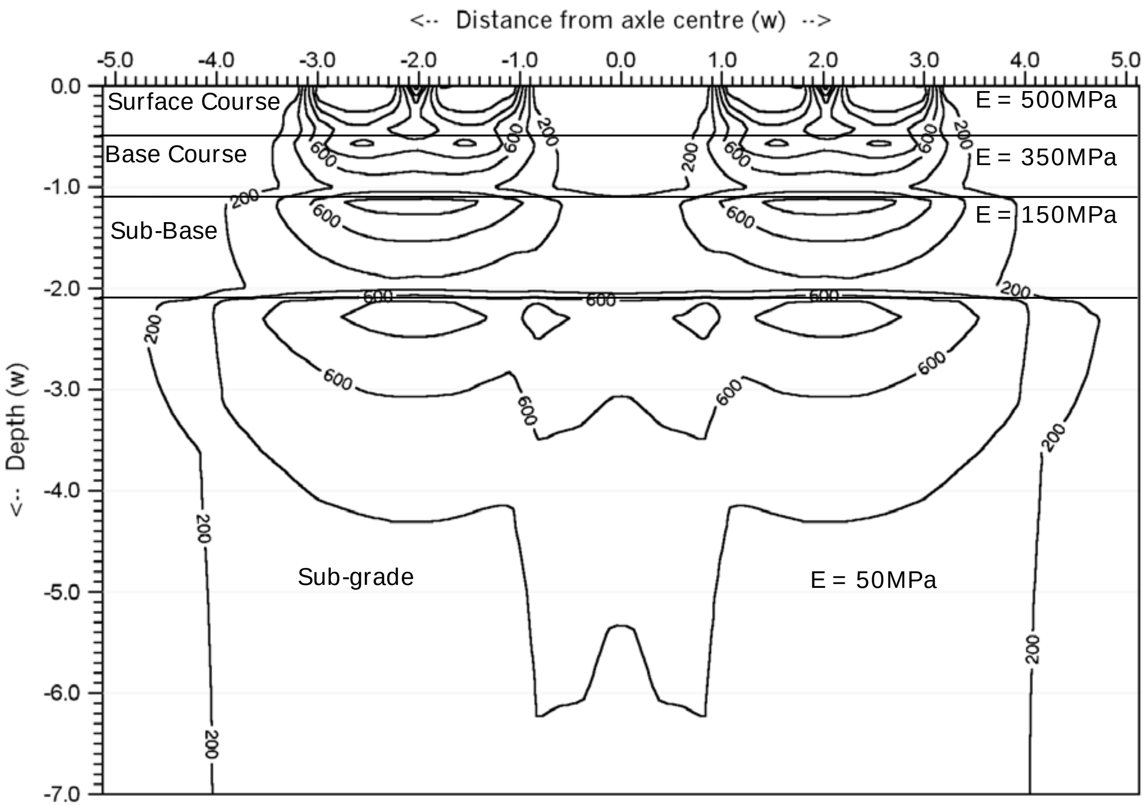



Figure 9-12 Vertical strain (in micro-strain) for four tires (pressure = 0.7MPa).

## 9.7 Summary and Recommendations

Although it is important that bearing capacity of the haul road construction material be greater than the stress generated by the load (tires), bearing capacity is seldom a limiting factor in most practical cases where crushed rock is used to construct the surface layer.

The most critical criterion for haul road design is the vertical strain. Apart from load geometry, vertical strain primarily depends on modulus of elasticity (strictly speaking modulus of rigidity, but modulus of elasticity gives a conservative estimate of modulus of rigidity as discussed in Section 3.3) and the thickness of various layers.

Once available construction materials have been analyzed for their properties, there can be many combinations of the materials. Laying the stiffest material on top and next stiffest material below it and so on gives best result in terms of least vertical strain.

Various possible layer thicknesses should be analyzed and the least thickness that gives vertical strain below the critical strain limit at all points, with some allowance for increase in strain due to tire interaction, should be chosen for road design.

The interaction of strain bulbs produced by adjacent tires on the rear axle of a truck resulted in a 20% to 80% increase in the maximum vertical strain in the base layer and below (the effect increased with depth) but had near zero effect on the maximum vertical strain in the surface layer. The interaction of stress bulbs generated by two pairs of tires at opposite ends of the rear axle of the truck has minimal effect on the maximum strain level at any depth but it deepens the resultant strain bulbs generated in the sub-grade. Strain bulbs generated by the front and the rear tires of a truck have little interaction.

If the maximum vertical strain in any layer in a road is much less than the critical strain limit (1500 - 2000 micro-strains), then the cover thickness above that layer can be decreased or less stiff material can be used. A strain analysis should be performed on the final road cross-section to confirm that the vertical strain at all points is still less than the critical strain limit with the new layer thickness and/or less stiff construction material(s).

# 10 QUESTIONNAIRE DETAILS

Table 10-1 General information.

| No.# | Mine | Time* worked (net operating hr./yr.) | | Ore handled (in million tonnes-kms / yr) | Waste handled (in million tonnes-kms / yr) | Largest truck used (payload) (tonnes) |
|---|---|---|---|---|---|---|
| | | Trucks | Road maintenance equipment | | | |
| 1 | Bullmoose Mine | 8520! | as required | 375,400 | 10,320,000 | 180 |
| 2 | Elkview Coal Corporation | 121,800 (at mine) 4,000 (at plant) | 33,200 | 20.017 | 158.625 | 218 |
| 3 | Highland Valley Copper | 158,448 | 8245 - 10,615 graders - 25,407 | 95.68 | 256.760 | 172 |
| 4 | Line Creek Mine | 83,130 | 23,000 | - | - | 216 |
| 5 | Luscar Mine | 125,000 | 25,000 | 20 | 40.000 | 234 |
| 6 | Mount Polley | 26,600 | 5,750 | 5.843 | 5.020 | 80 |
| 7 | Obed Mountain Mine | 8713 | 4782 | - | - | 153 |
| 8 | Poplar River Mine | 17,000 | 10,000 | 12.3 | no waste handled | 150 |
| 9 | Quintette Operating Corporation | 6,200! | 4,500! | 0.38 | - | 216 |
| 10 | Carol Lake Project | 130,000 | 40,000 | 40 | 7.500 | 179 |
| 11 | Stratmine Graphite Corporation | 15,000 $\pm$ 1000 | - | - | - | 35 |
| 12 | Syncrude | 250,000 | - | 175 | 395.000 | 290 |
| 13 | Greenhills Operation | 273,216 | - | - | - | 216 |

# mines referred by this number in other tables.

! hours per piece of equipment.

* cumulative hours (sum of hours worked for each piece of machine.

Table 10-2 Haul road construction materials and provisions for water crossing.

| Mine | Base Layer | Surface Layer | Water Crossing | Use of Imported Materials |
|---|---|---|---|---|
| 1 | 80% passing – 0.5m of run of mine rip rap of thickness as required | 80% passing -0.3m of same material as base layer | "U key" ditches to catch surface drainage for treatment, two culverts for stream crossing | pit run and contracted crush |
| 2 | pit run (free of mud) in variable thickness | crushed or fine pit run, thickness of application 25mm to 50mm | culverts for small drainage path, natural drainage paths are crossed by coarse free drainage material | no imported materials used |
| 3 | run of mine, 2m thick | crushed waste rock (-50mm), 0.5m thick | data not available | no imported materials used |
| 4 | pit run material consisting of a mix of siltstone, sandstone and shales | fine pit run using as much sandstone as possible, 2m thick | rock drains | geotextiles - Used to stabilize road fill in very wet area, covered by 2m of pit run material. |
| 5 | run of mine rock of size – 2m, thickness of application 3m minimum | run of mine rock of size -0.3m, thickness of application 0.5m | 0.61m (2 feet) culverts or where permitted, rock drains | no imported materials used |
| 6 | naturally segregated pit waste of size – 0.61m of variable thickness ranging from 1m to 10m | blasted waste rock from pit of size -19 mm, thickness of application less than 0.3 m | culverts and coarse rock drains | no imported materials used |
| 7 | sandstone, 10m thick | pit run gravel, 0.5m thick | data not available | no imported materials used |
| 8 | glacial till – in 0.15 m(max.) lifts, watered, bladed and packed, thickness – 1m (min.) | gravel – crushed to -50 mm, thickness – 50 mm (min.) | 600 mm (min.) diameter culverts | no imported materials used |
| 9 | run of mine - shale and sandstone of size – 1.5m, thickness of application - more than 3m | combination of run of mine shale (-80mm), plant coarse reject (-40mm), crushed run of mine (-30 mm), thickness <0.5m | culverts – accommodate 200 year return flow fill - run of mine (free of organic materials) | no imported materials used |
| 10 | bed rock – quarzite (sub grade) | run of mine–waste rock, treat rock | all drainage culverts – where applicable | no imported materials used |
| 11 | sub base - waste rock (size –1m), thickness of application: 1m<br>base - Crushed stone (size -63.5mm), thickness 0.3m to 0.61m. | crushed stone of size -19mm, thickness – less than 0.3m | data not available | calcium solution for dust suppression in summer time |
| 12 | sub-grade : 50mm of rut and roll fill<br>subbase : 1m of Pf sand in 350mm thick (loose) lifts.<br>base : 0.8m of pit run gravel in 500mm (max.) thick (loose) lifts | 0.8m of crushed gravel in 250mm thick (loose) lifts | crossings over ditches using 0.61m pipe, multiple pipe in high flow ditches | test pad of sulfur, tailing sand and lean oil sand |
| 13 | sandstone (blasted or in-situ) | -30 mm crushed sandstone | ditches, sumps | - |

Table 10-3 Road maintenance frequency.

| | Mine # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Clean / Regrade | Ex-Pit | NA | AR | C | D | D | AR | D | D | AS | D | BW | C | AR |
| | In-Pit | NA | AR | C | H | C | AR | D | D | AS | D | BW | C | AR |
| Repair | Ex-Pit | NA | AR | AR | W | BA | NR | AR | A | AS | D | NA | A | AR |
| | In-Pit | NA | AR | AR | BW | AS | NR | D | A | AS | D | NA | AS | AR |
| Dust Suppression | Ex-Pit | NA | DS | AR | BA | OS | OS | AR | DS | DW | DS | FW | DS | AR |
| | In-Pit | NA | DS | AR | C | TS | OS | AR | DS | DW | DS | FW | DS | AR |

NA – data not available
D – Daily
B – Biannual
A – Annual
AR – As required
H – Hourly
OS – Once per Shift
DW – Depends upon weather (every 2hr in summer)
DS - Daily during summer
W – Weekly
TS -Twice or Thrice per Shift
FW - Four times a week in summer
C – Continuously
BW - Biweekly
NR - Not Required

Table 10-4 Other haulage information.

| Mine No. | Truck dispatch system | Automated fleet condition monitoring | Runaway lanes | Speed limits |
|---|---|---|---|---|
| 1 | not used | Cat TPMS /VIMS | every 30m elevation @20-25% | main access - 15km/hr, service area - 20km/hr, in pit – 50km/hr |
| 2 | Modular | used | used | used |
| 3 | Modular | not used | used | 50km/hr |
| 4 | not used | not used | used | Variable |
| 5 | Modular | Modular | used on older long ramps | 35km/hr |
| 6 | not used | not used | not used | 30km/hr (8km/hr downhill loaded) |
| 7 | not used | not used | used | at ramps speed limit controlled by truck electrics - 40km/hr |
| 8 | not used | not used | not used | 80km/hr |
| 9 | not used | not used | used | 30km/hr for heavy vehicles |
| 10 | Modular | VSM | used | 30km/hr |
| 11 | not used | not used | not used | 50km/hr |
| 12 | not used | not used | not used | at intersections and congested areas |
| 13 | Modular | DDEC* | used | 45 kmph |

Table 10-5 Mines canvassed in the study.

| No. | Mine | Operator | Owner | Product | Average stripping ratio | Production (Mtonnes) | |
|---|---|---|---|---|---|---|---|
| | | | | | | Ore | Waste |
| 1 | Bullmoose Mine | Bullmoose Operating Corporation | Teck Corporation | metallurgical coal | 18.9 : 1 | 3.145 | 35.074 |
| 2 | Elkview Coal Corporation | Teck Corporation | Teck Corporation | metallurgical coal (mostly) | 8.1 : 1! | 3.0* | 24.456** |
| 3 | Highland Valley Copper | Highland Valley Copper | Cominco-50%, Rio Algom-33.6%, Teck-13.9%, Highmont-2.5% | copper and molybdenum | 0.87 : 1 | 47.5 | 41.3 |
| 4 | Line Creek Mine | Luscar Ltd. | Luscar Ltd. | coal | 6.52 : 1!! | 4.20 | 27.5** |
| 5 | Luscar Mine | Cardinal River Coals Ltd. | Luscar Ltd. + Consol Ltd. | coal | 10 : 1! | 2.8 | 29** |
| 6 | Mount Polley | Imperial Metals Corporations (IMC) | IMC and Sumitomo Corporation | gold and copper | 1 : 1 | 7 | 7 |
| 7 | Obed Mountain Mine | Luscar Ltd. | Luscar Ltd. | thermal coal | 7.29 : 1 | 1.5 | 19** |
| 8 | Poplar River Mine | Luscar Ltd. | Luscar Ltd. | lignite coal | 5.5 : 1 | 3.6 | 20** |
| 9 | Quintette Operating Corporation | Teck Corporation | Teck Corporation | metallurgical coal | 8.4 : 1 | 3.04* | 25.8** |
| 10 | Carol Lake Project | Iron Ore Company of Canada | North Limited | iron ore pellets & concentrates | 5.88:1! | 39 | 19 |
| 11 | Stratmine Graphite Corporation | Stratmine Graphite Corporation | I Metal Group (France) | graphite | 2.7 : 1 | 0.363 | 0.907 |
| 12 | Syncrude | Syncrude | several oil companies | oil sand | 0.8 : 1 | 160 | 100** |
| 13 | Greenhills Operation | Fording Coal Ltd. | Fording Coal Ltd. | metallurgical coal | 10.08 | 4.48** | 45.2** |

*clean coal
**in million bank cubic meter
! in bcm/cmt (bank cubic meter/ clean tonne)
!! in bcm/rmt (bank cubic meter/ raw tonne)