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DESIGN, CONSTRUCTION AND MAINTENANCE OF SURFACE MINE HAULAGE ROADS

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ABSTRACT

Often laborious evaluations are carried out to select mining equipment with little attention being paid to the design, construction and maintenance of the surface on which this equipment must travel. This paper deals with the many facets of designing surface mine haulage roads identifying elements which are critical to realizing the full potential and productivity of the equipment.

More specifically, the influence of grade and rolling resistances on truck productivity has been emphasized. Procedures for properly constructing and maintaining haulage roads have been summarized.

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CONCEPTION, CONSTRUCTION ET ENTRETIEN DES VOIES DE ROULAGE DANS LES MINES À CIEL OUVERT

par

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RÉSUMÉ

Il est fréquent que des évaluations laborieuses soient entreprises pour sélectionner de l'équipement d'exploitation minière sans tenir compte de la conception, de la construction et de l'entretien de la surface sur laquelle cet équipement doit se déplacer. Cet article traite des différents aspects de la conception des voies de roulage dans les mines à ciel ouvert, en identifiant les éléments qui jouent un rôle critique sur le plein potentiel et la productivité de cet équipement.

De façon plus spécifique, l'emphase a été mise sur l'influence de la résistance causée par la pente et le roulement sur la productivité des camions. Les procédures nécessaires à la construction et l'entretien adéquats des voies de roulage sont résumées.

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CONTENTS

TABLES

FIGURES

Design, construction and maintenance of surface mine haulage roads

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1 INTRODUCTION

During the past few decades, the surface mining industry has seen the off-highway truck capacity increase from 20 tonnes to 350 tonnes. Unfortunately road design, construction and maintenance procedures have not evolved at the same rate to promote safer and more efficient hauling. Typically, operating costs of hauling phase alone account for nearly fifty percent of total operating cost of a typical surface mining operation using trucks and shovels.

2 RAMP GRADIENT

In most hard rock mines, grades are generally adverse (i.e. against the loaded haul) thus increasing haulage cost per mile. Mine operators are faced with the problem of balancing increased costs against decreased distances effected by steeper grades and the increased construction cost of flatter roads. Furthermore laws and regulations may dictate a maximum sustained grade for safety reasons.

The dynamics of upgrade haulage can help a mine operator in selecting a grade that will minimize the truck travel time on a ramp.

Indeed, let us consider the following example:

- Truck type: CAT 777
- GVW = 300 000 pounds
- NVW = 130 000 pounds
- Flywheel power @ 1750 RPM = 870 HP
- Wheel power @ 1750 RPM = 660 HP (horsepower available for doing work at the area of contact between the driving wheels and the road surface. Wheel power ≃ 76% of flywheel power (1))
- Rolling resistance = 3%
- Coefficient of traction = 0.60
- Elevation difference = 500 feet

Now, if we assume a constant uphill speed and we use the small angle approximation (i.e. % grade = $\tan\theta \simeq \sin\theta$, where θ = slope of the ramp in degrees), we can then estimate the maximum attainable speed for various grades. The results are shown in Table 1.

Usually, the entrance speed will be greater than the maximum attainable speed shown in Table 1. In this case, a speed factor of 1 can be used to convert the maximum speed to an average speed (2) since the deceleration time is negligeable compared to the time the truck will travel at constant speed as shown in Appendix I.

Thus, dividing the length of the ramp by the average speed will give us the time it takes to haul the load uphill as shown in Table 1. The results show that the haul time is decreasing as the grade increases under the stated conditions. Similar calculations will have to be carried out for other truck types since the weight and the wheel power will be different for these trucks.

Now, we have to consider the return trip on the ramp. The grade resistance will become grade assistance but the rolling resistance will remain the same. In the conditions stated above, the total resistance force will become negative which means that the truck will have a tendency to accelerate. Therefore, the truck speed will have to be reduced and sustained for the duration of the descent.

Figure 1 shows the graph of the speed which a truck would pick up versus the delay time expended between the driver's perception of the need to reduce or control speed and the actual reduction of that speed. Appendix II shows the derivation of the formula used for the graph.

A reasonable operating grade speed can then be set up by using a safe maximum speed of say 20 mph (empty truck) and then substracting from it the speed which the truck would pick up during a given delay time. It should also be remembered that the steeper the grade, the less traction available for braking. For the driver comfort, the deceleratiem rate should not exceed 6 ft/sec^2 at 0% grade and this rate should be lowered proportionally with the increase in grade. At the other end of the scale, one could assume for instance that for a grade of 30%, the deceleration rate should be close to 0 ft/sec^2 meaning that it would be almost impossible to stop the truck.

The following reduced and sustained average speeds are assumed for the duration of the descent (brakes can safely handle these speeds):

	Grade (%)						
	4	6	8	10	12	14	16
Speed (mph)	18	17.5	15	14	12	11	9.5

With that information, the total time spent by the truck on the ramp can be calculated. The results are:

	Grade (%)						
	4	6	8	10	12	14	16
Haul time (mins)	12.1	10.3	9.5	9.0	8.6	8.4	8.2
Return time (mins)	5.7	4.7	4.7	4.7	4.7	5.1	7.1
Total time (mins)	17.8	15.0	14.2	13.7	13.3	13.5	15.3

The results are depicted in Figure 2. The conclusion is that this particular type of truck could perform pretty well on any reasonable grades. Other factors will have to be considered like the increase in the number of gear reductions and brake component wear as the grade increases, increase fuel consumption and construction cost as the grade decreases, ice and snow problems which might reduce the grade to a small value say 6%. It should be noted that the speeds assumed for the duration of the descent are about 60% of those that can preclude service brake failure. In reference 3, stopping distance curves can be found for various grades, speeds and weights in each Society of Automative Engineers (SAE) test weight category.

3 INFLUENCE OF ROLLING RESISTANCE (R.R.) ON TRUCK PRODUCTIVITY

An important measure of haul road condition is rolling resistance (R.R.). This is the amount of drawbar pull or tractive effort required to overcome the retarding effect between the tires and the ground. Rolling resistance is composed of three components

- internal power train friction
- tire flexing under load
- tire penetration

The part of the rolling resistance will be a constant for a given load, whereas the part due to haul road surface will vary with the haul road type and its condition.

An equation (Carterpillar) giving R.R. at 0 mph is (4)

R.R. in % = 2% + 1.5% x tire penetration (inches)

Another factor that adds to rolling resistance is air resistance acting when the vehicle is in motion. For example, Caterpillar Co. uses in its computer programs an increase in rolling resistance of 0.025%/mph for vehicles in the 0-40 mph speed range. This would mean an increase of 1% in rolling resistance for a vehicle travelling at 40 mph. This also means that high power to weight ratio equipment are being "penalized" with higher resistance when travelling at their top operating speeds.

Another component of rolling resistance, often ignored is road deflection. It is estimated that for concrete it is .03 in, for cold asphalt it about .06 in and for very hot asphalt is can be as high as 1 in.

In practical terms, the influence of rolling resistance is best illustrated by an example (Table 2). In this case a fleet of 85 tonnes trucks is sized using Caterpillar's VEHSIM program. Five million tonnes of overburden are to be transported to a fixed dumping site along a specified haul route. The only variable in this exercise is the rolling resistance which varies from 4% to 16% in four equal steps. The output from the VEHSIM program is summarized in Table 2 (5). Comparing the performance data for 4% R.R. with that for 16% R.R. it is noted that

- the hourly production at 16% R.R. is approximately 53% of that obtained at 4% R.R.
- the number of trucks required at 16% R.R. is twice the number required at 4% R.R.
- annual operating cost of the truck fleet at 16% R.R. is approximately twice that of 4% R.R.

This example clearly demonstrates that haul road rolling resistance can have a significant effect on mine production.

4 LOAD BEARING CAPACITY (LBC)

The load bearing capacity of a soil is directly related to its shear strength and is given by the well known Coulomb's equation:

$$s = c + (\sigma - u) \tan \phi,$$

where,

s = shear strength,
c = cohesion,
σ = normal stress on the sliding plane,
u = pore-water pressure,
ϕ = friction angle.

Table 3 lists some typical values of bearing capacity of some soils. Table 4 lists the ground pressures exerted by the off-highway trucks in the range of 85 to 170 tonnes capacity. The tire loading of a 170 tonnes and 85 tonnes truck is 72 psi and 84 psi respectively. It is clearly seen from Table 4 that any material which is less consolidated than soft rock will not provide a stable base for the haul road and other materials will be required to be placed over the subgrade to adequately support the road surface.

Since the tire loading is dependent on the number of tires, size, ply rating, inflation pressure and overall vehicle weight some relief might be obtained by modifying any of these variables. Table 3 also shows, as would be expected, that with reduced payload vehicle ground pressure is also reduced falling within the range of load bearing capacity of some soils.

5 CALIFORNIA BEARING RATIO (CBR)

One method of determining the amount of additional material which should be placed over the subgrade is through use of CBR curves. As shown in Figure 3 sub-base thickness is determined by vehicle load as well as soil type. Such curves were utilized by the authors in a haul road design study carried out for an oil-sands operation (6). Figure 4 illustrates the two cases examined. In case 1 clay material was available in sufficient quantities and was to be utilized in road building whereas case 2 assumes plentiful availability of sand. From table 5 it is seen that in each case the 8" crushed rock layer could be replaced by a layer of pit run gravel.

6 TIRE PRESSURE

One of the important factors governing the magnitude of R.R. is the tire pressure. Since rolling resistance is proportional to the depth of penetration, a high pressure tire is better on a hard surface because there is no tire penetration and the rolling resistance is mainly due to flexing of the tire walls which is very small. A low pressure tire on the other hand is better for equipment operating on soft ground because it creates low penetration.

It is important to recognize that tires are an expensive item and the costs form a significant portion of the mobile equipment's operating cost at a surface mine. Well designed and maintained haul roads are vital to improve tire life. Tire pressures are critical and ought to be maintained at their optimum which is dependent on the rolling conditions. As an illustration a tire which is 10% underinflated to its specifications loses about 10% of its total life mileage. It is recommended that every surface mine should prescribe tire pressures for its fleet depending on vehicle type, load carried, haul road condition and season of the year.

7 SOIL STABILIZATION TO IMPROVE LBC OF SOILS

The load bearing capacity of soils can be improved by application of soil binders resulting in reduced rolling resistances. Table 6 lists the various types of binders used or proposed on surface mine haul roads. It is known that some stabilizing procedures have already been used with mixed results. Soil cementing and bitumen impregnation are more expensive but have been used with success. Calcium chloride and hydrated lime are inexpensive but reportedly not as effective.

8 CORRUGATION OF HAUL ROADS

Corrugations can afflict almost any surface subject to rolling or sliding motion. They can be seen on roads (paved or unpaved), railway tracks, bearings, etc. The corrugated surface often called "washboard" comes from the rythmical bouncing of the equipment wheels on an unpaved road. Sound explanations of that phenomenon can be found in a paper written by Mather (7).

The main conclusions of the author are:

- Corrugations are not generated until a critical speed of 4 mph is reached since the tire scrubbs the surface below that speed.
- Speed is a major factor in building up corrugations after 4 mph.
- Road corrugations are "dry weather" effects.
- Corrugations always tend to form first at irregularities on the surface of the unpaved road.

The problem of road corrugation can be permanently cured by paving. This solution however is not practical for most mining operations except for permanent service roads. Instead, grading and watering are the temporary solutions sought to solve the problem. However, the efficiency of grading and watering will be influenced by road design and layout.

9 HAUL ROAD DESIGN AND LAYOUT

Some salient points to be considered when designing haul roads are:

- At all times, the operator should be able to see ahead a distance at least equal to the required stopping distance.
- Sharp horizontal curves should be avoided at the top or at the bottom of a ramp.
- Intersections should be made as flat as possible and should be avoided at the top of a ramp.
- For a two-lane haul road, the minimum width should be 3.5 W, (W is the width of the largest truck in the mine). This width should be increased for safely negotiating sharp curves by allowing for passing lanes and safety berms.
- The difference in elevation between the road edges should be 1/2 inch per foot for proper drainage.
- Curves should be superelevated in the range of .04 - .06 foot per foot of road width depending on the curve radius and the equipment speed.
- The curve radius should exceed the minimum turning radius of the equipment.
- For drainage, V-ditch configurations are recommended. The slope should not exceed 2:1.

10 MAINTENANCE OF HAUL ROADS

In order to keep the road surface smooth, thus reducing rolling resistance a mining operation generally uses graders. Graders are also used to remove the snow, to keep ditches clean, to build roads and to remove loose rock from the roads. Under normal condition, a haulage road can be satisfactorily maintained with one operating grader for approximately 30 000 tonne-mile of daily haulage (8).

Water trucks are used mainly in summer months to keep the dust down and also to help compaction of haul roads. Incorporation of chemicals can help in obtaining a firm, hard-packed wearing surface with smoothness and riding qualities. During summer months, it is estimated that a road requires between .2 and .5 gallon of water per square yard of surface per hour to keep the dust down depending on the nature of the road surface, the intensity of the traffic, the % of humidity and the amount of precipitation.

Scrapers are an excellent piece of equipment for road building. They are capable of spreading their load into smooth low lifts and can place material selectively. Material should be placed in lifts - usually 8 to 10 inches and should be well compacted while moist to achieve maximum density. Soil compaction can be achieved by pressure, vibration, impact and aeration. In practice a combination of these methods is used.

11 GENERAL DISCUSSION

It must be recognized that the development of haulage roads is much more than just clearing existing terrain. The selection of an appropriate grade, profile and road surface must be made based on mine plans and economics considering the size and type of equipment to be used at the mine. Optimum solution is not easy to derive because of the many conflicting parameters and difficulties in estimating associated costs. However, poor road design and maintenance always lead to undesirable results such as lower productivity and higher equipment operating and maintenance costs.

In cases of long life pits and haul roads it might be more cost effective to build secondary highway type paved roads. This aspect should be evaluated for a mining operation on site specific basis.

Many of the older Canadian surface mines are designed for truck haulage. Trucks provide the flexibility required in a surface mine and can operate in confined spaces. For both of these reasons, in spite of availability of a variety of conveyor systems, off-highway trucks will continue to be used in surface mining. Their productivity is greatly dependent on the haul road condition. Poorly maintained roads or roads surfaced by weak materials are characterized by an increase of rolling resistance, poor trafficability and lower productivity.

It should be emphasized that there should be a systematic program of haul road condition monitoring at every mine including periodic measurement of rolling resistance. Proper compaction of road, grading, watering, adequately inflated tires, maintaining truck loads to within manufacturer's design specifications, use of radial tires, and proper sizing of tires will all contribute to lowering of rolling resistance and enhancement of equipment productivity (9).

Another avenue proposed to increase productivity is to reduce rolling resistance by the application of chemicals that improve the road surface. Some unconsolidated soils can be stabilized to a certain degree that will accommodate the weight of some vehicles. In some cases application of binders will result in significant reduction in the quantity of base material required in road construction whereas in others binders mixed with subgrade soil can be used directly as a road surfacing material.

More field oriented research is needed on the application of soil binders. Likewise application of geotextiles in road construction must be also examined. Application of both of these technologies to mine haul road construction can result in improved vehicle performance, extended road life and greater productivity.

The grade of haul roads is equally important. However, the haul road grade just as the positioning of haul roads is often dictated by the mine plans which are based on the geology of the deposit and the production requirements. Nonetheless mine planners must appreciate the significance of pit haul road network on mine economics. With each set of mine plans the influence of haul road location, grade and rolling resistance on mine economics and daily operating cost must be critically examined.

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APPENDIX I

TRUCK TRAVEL TIME TO ASCEND A RAMP

In actual operations it is important for a truck to approach an adverse grade at the highest possible speed within the limits of safety. Let us assume that the initial speed is 20 mph and that the slope is 8%.

We can use the following general equation:

Kinetic energy at the beginning of the ramp + work of the engine - work of the total resistance = Kinetic energy at maximum attainable speed.

Using the same data given previously we have:

Total resistance = 33 000 pounds
Ramp length = 6 250 feet
Truck weight = 300 000 pounds
Speed of entry = 1 760 ft/min.
Wheel power = 660 HP
Maximum attainable speed = 660 ft/min.

The equation for energy conservation now becomes:

$$\frac{300\ 000 \times 1\ 760^2}{231\ 840} + (t \times 660 \times 33\ 000) -$$

$$33\ 000\ d = \frac{300\ 000 \times 660^2}{231\ 840}$$

where t = deceleration time, min.
d = deceleration distance, feet

but d = average speed x time
= (1 760 + 660) x .5 x t = 1 210 t

Substituting in the previous equations, we obtain:

t = 0.190 min.

and d = 230 feet

The time for travelling the remaining distance at maximum attainable speed is then equal to 9.12 mins (i.e. (6 250 - 230)/660).

The exact total time to ascend the 6 250 foot ramp is therefore 9.31 mins. This result compares favorably with the one obtained in Table 1 which was 9.5 mins by assuming a constant speed of 660 ft/min.

The use of a speed factor of 1 is thus appropriate.

This method is precise but not as practical as the one given in the text. Note that the deceleration time represents about 2% of the total time.

APPENDIX II

AMOUNT OF ACCELERATION

To calculate the amount of acceleration achieved as a function of grade and delay time, we can use the following equation:

F = WA/g

where,

F = force accelerating the truck, pounds
W = truck weight, pounds
A = acceleration, ft/sec^2
g = constant of gravity, ft/sec^2

Using the following assumptions:

- Small angle assumption i.e. % Grade = tan $\theta \simeq$ sin θ, where θ is the slope angle in degrees.
- Rotational inertia adds about 14% to translational inertia, we obtain the following expression:

A = .1926 x effective grade (%), mph/sec
where effective grade = % grade - % rolling resistance.

Table 1. Maximum attainable truck speeds for various grades

	GRADE (%)						
	4	6	8	10	12	14	16
Elevation difference (feet)	500	500	500	500	500	500	500
Ramp length (feet)	12 500	8 333	6 250	5 000	4 167	3 571	3 125
Grade resistance force (pounds)	12 000	18 000	24 000	30 000	36 000	42 000	48 000
Rolling resistance force (pounds)	9 000	9 000	9 000	9 000	9 000	9 000	9 000
Total resistance force (pounds)	21 000	27 000	33 000	39 000	45 000	51 000	57 000
Work (foot-pounds x 1000)	262 500	224 991	206 250	195 000	187 515	182 121	178 125
Max. attainable speed (mph)	11.8	9.2	7.5	6.3	5.5	4.9	4.3
Speed factor	1	1	1	1	1	1	1
Haul time (mins)	12.1	10.3	9.5	9.0	8.6	8.4	8.2

Notes:

Work = Total resistance x ramp length.

Max. attainable speed = 375 x wheel power/Total resistance, where 375 is a conversion factor.

In all cases, traction force is greater than total resistance force.

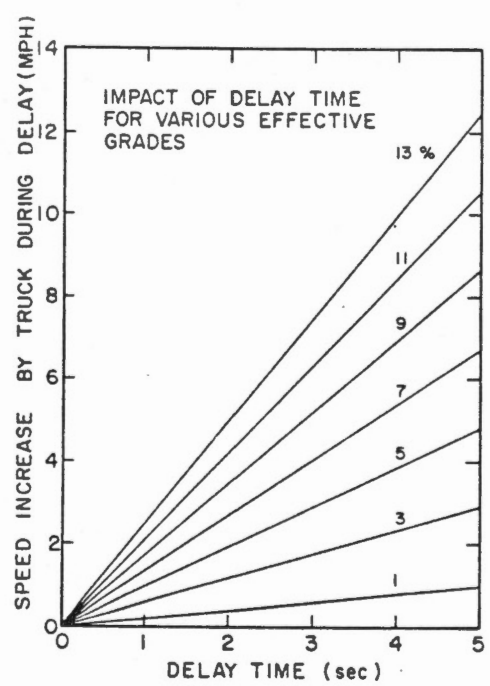

Fig. 1 - Speed Increase on a Ramp as a Function of Delay Time.

Table 2. Influence of Rolling resistance on off-highway truck performance

Truck : Carterpillar 777 Empty Weight : 130000 Lb
Payload : 1700000 Lb Tires : 27x49
Haul Road Grade : 7%

Haulroad Specifications		Production Estimation vs. Rolling Resistance (%)				
Segment No.	Distance (Ft.)		4%	8%	12%	16%
1	500	Fixed Time (Min.)	1.5	1.5	1.5	1.5
2	1500	Haul Time (Min.)	17.75	25.25	32.98	39.34
3	1000	Return Time (Min.)	6.32	6.32	6.34	7.25
4	1400	Cycle Time (Min.)	25.56	33.07	40.83	48.09
5	3500	Trips/60 min. Hour	2.35	1.81	1.47	1.25
6	4150	Payload (TONS)	85	85	85	85
		Production (TONS) /60 min HR	199.47	154.22	124.92	106.04
		Annual Production/ Truck (4818HR) X 10^3 TONS	961	743	602	511
		Annual Production (X 10^3 TONS)	5000	5000	5000	5000
		Number of trucks needed	5	7	8	10
		Capital Required (X 10^3 $)($700,000 per truck)	3500	4900	5600	7000
		Truck Operating Hours (Production 5000 X 10^3 TONS)	25064	32421	40026	47152
		Annual Fleet Operating Cost ($60/HR) ($ X10^3)	1503	1945	2402	2829

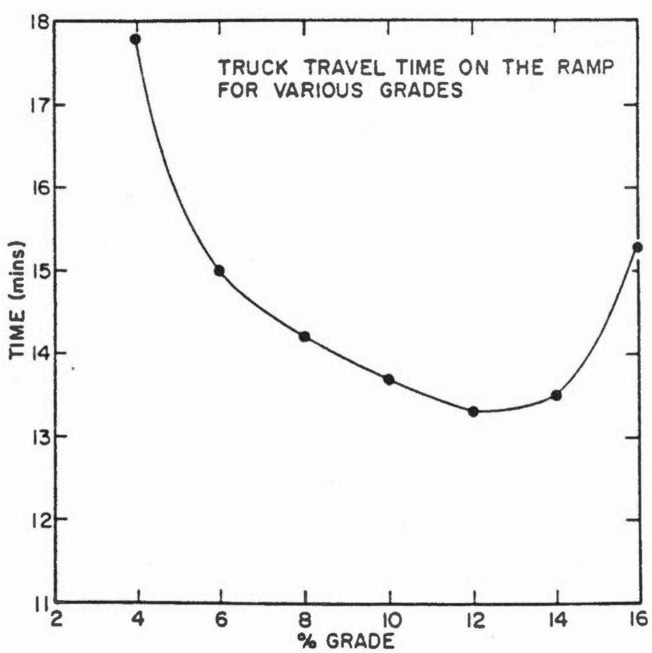

Fig. 2 - CAT 777 Travel Time on a Ramp as a Function of Grade.

Table 3. Typical Bearing Capacity of Soils

MATERIAL	LOAD BEARING CAPACITY (PSI)
Hard rock (sound)	830
Medium hard rock	550
Compact gravel	140
Soft rock	110
Loose gravel, compact sand	80
Oil sands "in situ"	70
Compact clay	55-70
Compact sand-clay soils	40
Silt	30
Loose fine sand	28-30
Firm or stiff clay	20
Soft spots	14

PSI = pounds per square inch.

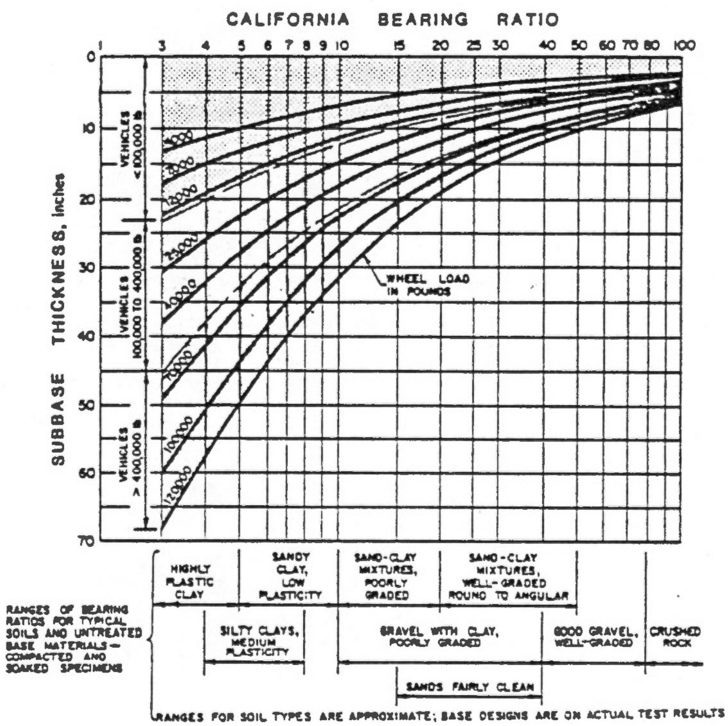

Figure 3. Typical California Bearing Ratio Curves

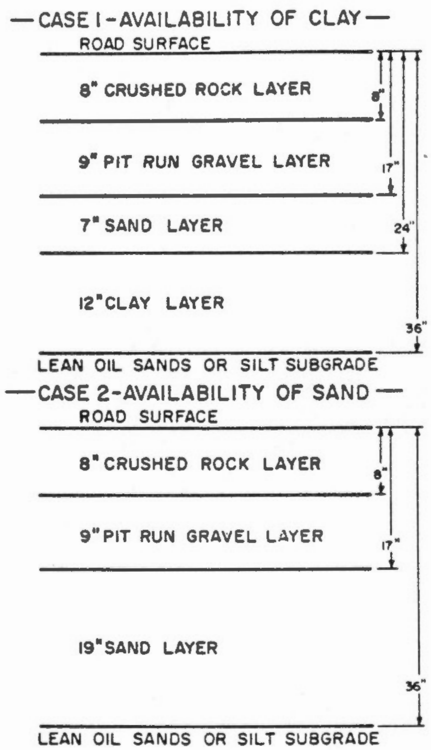

Fig. 4 - Examples of Application of CBR Curves.

Table 4. Typical Ground Pressures Exerted by Off-Highway Trucks

	Manufactuer's Payload			Payload-75% of rated payload data to follow factored accordingly		
	85t	100t	170t	85t	100t	170t
Manufacturer's recommended payload	79 tons	95 tons	142 tons	63.75	75	127.5
Tire size and tire contact area (in^2)	24:00-49 537	30:00-51 820	36:00-51 1181	24:00-49 537	30:00-51 820	36:00-51 1181
Front axle weight (lb)	89364	111837	167607	72113	88292	150492
Rear axle weight (lb)	818436	227063	340293	146412	179260	255220
Front ground pressure per tire (psi)	83	68.1	70.9	67	53.8	63.7
Rear ground pressure per tire (psi)	84	69.2	72.0	68	55	54

Table 5. Thickness of Subbase Materials

MATERIAL	CBR	REQUIRED DEPTH BELOW SURFACE (TOP OF MATERIAL)
Lean Oil Sands	5	36"
Clearwater Silt	5	36"
Boulder Clay	10	24"
Sand	15	17"
Pit Run Gravel	40	8"
Crushed Gravel	40	8"

Wheel load of 70 000 pounds has been used for the calculations.

Thicknesses are determined by equipment wheel load as well as soil type. For a tandem axle, the wheel load value should be increased by 20%.

Table 6. Summary of Soil Stabilizing Procedures

Procedure	Remarks
Cement	3-16% by weight. mixing redure requirements. except heavy clays and organic matters. cementing effect.
Hydrated lime	2-8% by weight. plastic soils Ip 10-50. *
Bitumen emulsions (impregnation)	for granular size. hot and cold technology.
Chemical	transformation of soils.
Calcium chloride	thaw frozen soils. corrode equipment reduce Ip of soils.
Phosphoric acids	increase strength and water resistance of soils. not to be used in soils with calcium chloride.
Polymers	expensive catalyser and monomer. future potential.
Other products	resins, calcium acrylate, aniline forfurol, sulphur liquors, etc.

* I_p = Plasticity index , also designated as PI