A SURVEY OF DESIGN, CONSTRUCTION, AND OPERATION PRACTICES FOR STEEP ROADS IN THE OREGON COAST RANGE

by

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The selection of a road standard is a complex decision involving consideration of design, construction, maintenance, and vehicle operating costs. The first step in any analysis involves a definition of the physically feasible alternatives. In the Oregon Coast Range, a combination of steep topography and sensitive soils influence the type of physical options available to management. To reach the necessary landings for harvest operations with the minimum road lengths, requires steep roads. The conditions for successful operation of steep roads have not been documented.

This paper summarizes the effects of road gradient upon excavation, drainage, road surfacing, haul, and maintenance based upon information available from transportation planners, materials engineers, maintenance supervisors, logging contractors, and equipment operators. The physical aspects of soil-vehicle interactions and vehicle performance are investigated to a limited degree using laboratory and field tests. An economic framework for comparing the costs of steep roads is included. Subject areas where limited information is available are suggested for future research.

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I. INTRODUCTION

Objective

One of the questions faced by forest resource managers is the determination of the optimal transportation system to meet management objectives. A logical procedure is to define the feasible alternatives, calculate the quantifiable cost of each alternative and identify non-quantifiable impacts. In the steep mountainous terrain in the Oregon Coast Range, there is increasing interest in the construction of steep roads to avoid problems in slope stability and sediment from erosion. In the literature however, there is little guidance to define the technical and cost relationships upon which to evaluate the feasible alternatives.

This paper will review the economic framework to evaluate differences between road alternatives, summarize available technical and cost relationships between road components and gradient and suggest future research needs.

Scope

The focus of this paper is on the design, construction and operation of steep roads. The intent is to summarize the design, construction, and operation practices for steep roads in the Oregon Coast Range. As the research is constrained by both budget and time, certain limitations were necessary. These limitations include:

1. Other than the literature search, information was primarily collected from personal communications with knowledgeable sources in the area and available unpublished documents.

2. The laboratory and field testing data and conclusions are limited to soil types and moisture conditions commonly found in the Siuslaw National Forest.

3. The vehicles studied are limited to stinger-steered log trucks and assist vehicles common to the Oregon Coast Range.

4. The gradeability models apply to straight road segments with equal soil conditions under each tire and the load is equally distributed between tires on the same axle.

5. Truck drive trains are assumed to be designed to deliver the torque associated with the maximum engine torque.

Study Procedure

To accomplish the objective of the study within the scope outlined above, the following tasks were undertaken.

1. A literature review was done to identify the state-of-the-art in steep road construction.

2. Interviews were conducted with the Forest Service and the BLM, logging contractors, and members of the civil engineering and forest engineering departments at Oregon State University.
3. After literature review and interviews were completed, a second literature review was undertaken to study road components that were affected by grade. Relationships between road grade and excavation, vehicle performance, drainage, surfacing and maintenance were summarized.
4. A cost function for identifying road cost differnces between steep road alternatives was prepared.
5. For road components where the second literature review was not productive, limited field and laboratory testing was done to provide additional insight. These included field moisture and density tests, laboratory soil shear tests and soil/rubber shear tests.
6. Areas for future research were identified.

II. PROBLEM DEFINITION

The determination of the optimal road standard is a common problem for the transportation planner. It requires an identification of feasible alternatives, a cost evaluation, and the selection of the preferred alternative. In some cases, after consideration of the feasible alternatives, engineers have decided to build steep roads. Once steep roads are accepted as a option, the need arises to identify physical relationships that would affect the feasibility and cost of steep roads. Many questions must be answered. What is the maximum grade an unassisted log truck can negotiate and what is the maximum for assisted log truck travel? What components of road design, construction and operation including maintenance are affected by road grade?

Management Objectives

Important objectives for management of forest land in the Oregon Coast Range include the maintenance of a quality environment and the production of timber products. Road building is a vital part of timber harvest in the Pacific Northwest. Some of the management objectives for the nearby Siuslaw National Forest are: 1. Emphasize quality performance in all management practices; 2. Adopt practices to minimize con-struction of permanent facilities, such as roads and buildings; and 3. Manage municipal watersheds for other resources when consistent with maintenance of Class I stream standards. Management decisions are made within the framework of this environmental responsibility.

Decision criteria

Management decisions about road building must consider the environmental cost, the physical feasibility and the economic feasibility of all road options. All other things being equal, the lowest cost alternative is chosen. The cost model presented in this paper provides a framework for these decisions.

Feasible Alternatives

To be feasible, the alternative must satisfy the management objectives. The manner in which elements of road building vary as a function of grade is not well documented. Assessing the feasibility of steep road options is made more difficult by this lack of documentation.

Cost Functions

To identify the lowest cost alternative which is feasible and meets management objectives, requires an understanding of the relationships between road components and costs. The effect of road grade on excavation, surfacing, drainage, haul and maintenance needs to be quantified. A framework relating these factors is necessary to identify how each factor relates to the overall problem.

Literature Review

Road grades steeper than 20% are becoming increasingly common in the Pacific Northwest and elsewhere around the Pacific Rim. Blackman (1984) reports that in the Oregon Cascades a logging operator was hauling on adverse grades of 32% with a tractor assist. Fraser (1979) reports that in Indonesia a logging firm was using 6 x 6 log trucks to haul on adverse 28% grades. Baumgras (1971) inventoried the curvature and grade of Appalachian logging roads and found that eastern logging roads were as steep as 25%. I could not, however, find literature that describes how to design, construct, or operate on roads steeper than 20%. Guidelines that are available are most commonly expressed as standards.

Standards

Manuals and textbooks commonly recommend maximum adverse and favorable grades (Forbes, 1955; Whackerman, 1966; Stamm, 1950; Pearce, 1977). The recommended maximums vary for different road classes and between sources. The steepest recommended maximum adverse grade from these sources is 18%. These authors do not provide a rationale for their standards although undoubtedly evaluations were made at the time the standards were set. Byrne et al., (1957) suggest that an evaluation of different road grade alternatives be made based on economic considerations.

Gradeability

The Western Highway Institute (1976), Stryker (1977), McNally (1975) and Fitch (1976) present uphill gradeability formulas that make some simplifying assumptions about the configuration of the vehicle and weight on the driving wheels. Sessions (1984) presents a more complete analysis including the dynamic weight transfer between axles and rolling resistance. Similarly, downhill traction limited gradeability has not received much attention.

Rocking practice

Vischer (1979, 1982) and Yoder (1967) discuss design methodology for crushed rock aggregate pavement design. However, they do not specifically address aggregate design for steep roads.

Summary

The need for better information about the physical feasibility and costs of steep grades is clear. This study will attempt to consolidate available information and identify needs for future research.

III. ROAD COMPONENTS AFFECTED BY GRADE

Clearing and Grubbing

Clearing and grubbing to clear the right-of-way of organic matter to prevent contamination of road fills is the first step in road construction.

Clearing and grubbing requires felling the timber and removing the merchantable material. The unmerchantable material can be removed or disposed of in a number of ways.

Cost per acre of clearing and grubbing varies with size and density of forest cover, side slope and intensity of disposal required. Costs can range from $6000 per acre to less than $1000 per acre of road right-of-way (Nigier, 1984).

The number of horizontal acres per mile of clearing and grubbing depends on the width of the road and the side slope that the road is being built on. Width of clearing and method of disposal are usually a matter of policy and may vary considerably (see Figure 1).

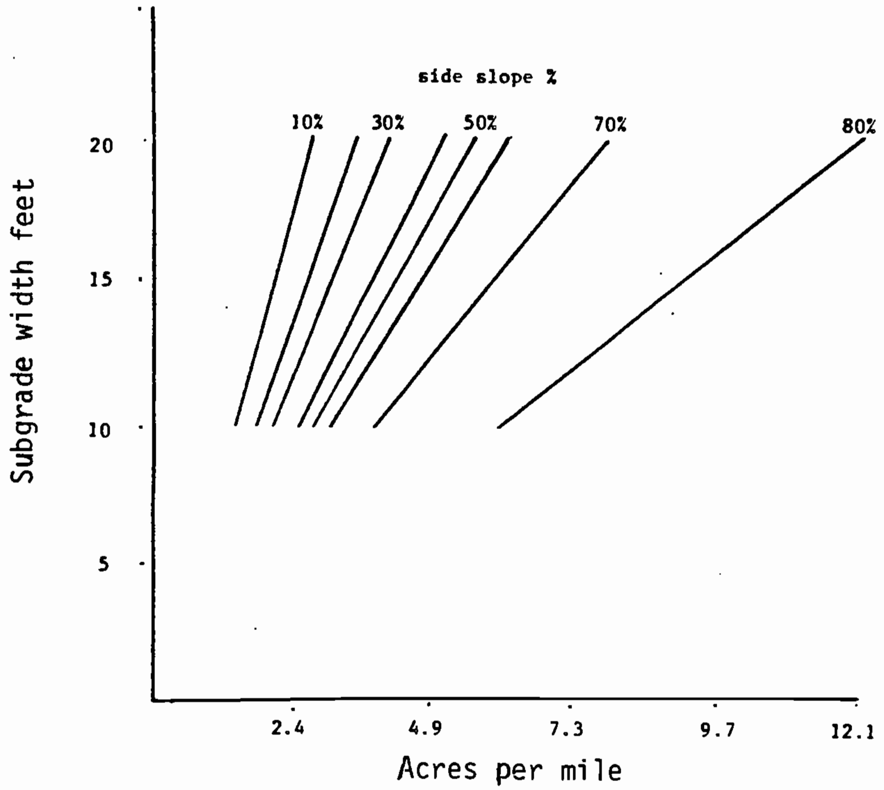

Figure 1. Horizontal acres as a function of slope

Excavation

Introduction

Currently, design engineers in the Coast Range are using steep grades to minimize sidehill construction. The cost of excavation and ultimately the viability of a road option may depend on excavation volume and the difficulty of removing it. On steep slopes, full bench roads are constructed so that very little of the excavated material is used to support the road surface. Full bench construction on steep slopes creates a large volume of material that, if required to be hauled from the site can considerably increase the cost of the road.

Excavation volumes for sidehill construction are proportional to the ground slope and vary as the square of the subgrade width. In other words, if the ground slope doubles the excavation volume will increase proportionally. If the subgrade width doubles then the excavation volume will increase four times.

Figure 2 shows the increase in excavation volume for various subgrade widths and side slopes. Volumes of excavation in cubic yards per 100 feet of road is plotted against subgrade width in feet. Each line represents a single ground slope. It can be seen that even for fairly moderate ground slopes (30 percent to 40 percent) as road width increases excavation volume increases rapidly.

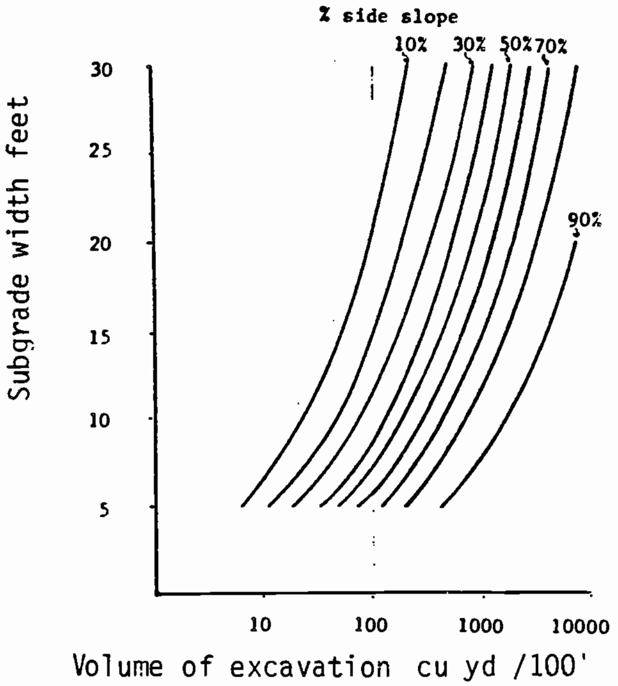

Figure 2. Excavation required for full bench construction as a function of subgrade width and side slope.

The cost of excavation and removal of the excess excavation material has been one of the driving forces for placing roads on ridgetops, where soil volume to be excavated is at a minimum. Satisfactory disposal sites for excavated material are difficult to find in the Oregon Coast Range. Typically, the side slopes are steeper than 70% or 80% and the topography is so rugged that there are few places to dispose of excess excavation.

To keep road locations on the ridge tops, designers are forced to use grades steeper than 20%, in some cases greater than 30%. Several tradeoffs for reduced excavation include increased operating costs, assisting vehicles, problems with surfacing, and increased potential for road surface erosion.

Excavation volumes are a function of road length, road width, and steepness of side slope. Road length between control points is a function of road grade. In general, a reduction of road length will reduce excavation. This is illustrated in the following example comparing the cost of two alternatives. Consider a road to be built on or near the top of a ridge to a landing at the end of the ridge. There is a rise in the middle of the ridge. Alternative 1 is to go straight over the top of the rise, while Alternative 2 goes around the rise at a constant 18 percent.

Alternative 1 would require two segments of steep grade to stay on the ridge, 850' of favorable 30% and 260' of adverse 28% the total length for that option was 2150'. Side slopes on the ridge top would be 15 to 30% sloping away from the road on both sides.

Alternative 2 would require 2900' of 18% favorable grade with side slopes that start about 30% go to 100% and then go back to 55%.

The road length for the road with steeper grades is 26% shorter than the road that held a constant 18% road grade. The volume of excavation for the ridge top road was less than 1000 yards while the volume of excavation for the sidehill alternative was about 32,000 yards. If we assume sidehill construction alternative would require removal of 90% of the material from the site (end hauling) and that the nearest disposal point is 10.3 miles away. Costs would be about 3.3$/yard[1] for excavation of common material and a 10-mile haul. At $3.30 the cost of 28800 yards is $95,400. Thus, the end hauling requirement would increase costs roughly $171,000/mile.

Steeper road grades generally allow designers to use more options to shorten road lengths and minimize excavation and end hauling costs.

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[1] $3.3/yard was a recent bid on the Mapleton District, USDA, Forest Service for excavation and a 10-mile end haul.

Rocking Costs

General

The bedrock in the Oregon Coast range is made up of sandstone, mud stones and silt stones, and scattered pockets of basalt.[2] Since there is little good quality road rock available this often means that the rock will have some undesirable characteristics.[3]

Because of the wet weather in the Oregon Coast range, roads that are intended for year-round use or use during the wet season require some surfacing. For low volume roads that must remain open or be used in wet weather, crushed rock aggregate has been one of the major surfacing methods. Vischer, in his report "Assessment of Surface Aggregate requirements and specifications," has recommended that surface aggregates have a unconfined compression strength

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[2] Soils that are produced from this parent material are predominately sand or silty sand with little or no plasticity.

[3] Some of the rock used for crushed rock aggregate is dredged from one of the local rivers. The dredged material tends to be small in size and therefore, has poor fracture. It is also clean (zero PI.) with little minus 200 material. The crushed material will not meet standard aggregate surfacing specifications for PI and fines content. The material does not bind together and therefore performs poorly as a surfacing aggregate (Moore and Williamson 1983). The rock from other quarries in the area has similar problems, consistently producing surfacing aggregate that runs about 3 percent fines and has zero PI. This meets base course aggregate specifications but does not have enough binder to perform well as a surface aggregate.

of 75 psi. The recommendation is derived from results of laboratory tests and field observations. From his tests and observations, he found that a well graded aggregate with about 7% to 12% passing the number 200 sieve is likely to produce a surface course with an unconfined strength of 75 psi. Vischer explains his use of the unconfined compression test by pointing out that a traditional method of obtaining surfacing strengths (The California Bearing Ratio Test) measures a confined stability of a material and often gives questionable results in granular materials. He also points out that unconfined compression tests are simpler, less time consuming and more applicable for a surface aggregate than the CBR test. Vischer outlines a procedure for preparing samples for the unconfined compression test. First, three specimens are molded at or near optimum moisture content with the standard T-99 compactive effort in 4-inch molds. Next, the specimens are cured in an oven at 140°F for 48 hours. Then the specimens are tested in compression at a load ratio of from 1 to 2 $lbs/in^2/sec$. If the average unconfined compressive strength of three specimens is greater than 75 psi, then Vischer concludes that the mixture should perform acceptably as a surfacing material.

Figure 3 shows unconfined compressive strength as a function of percent passing the #200 sieve. Most of the base course aggregate mixtures mixtures specify 0-10% passing the

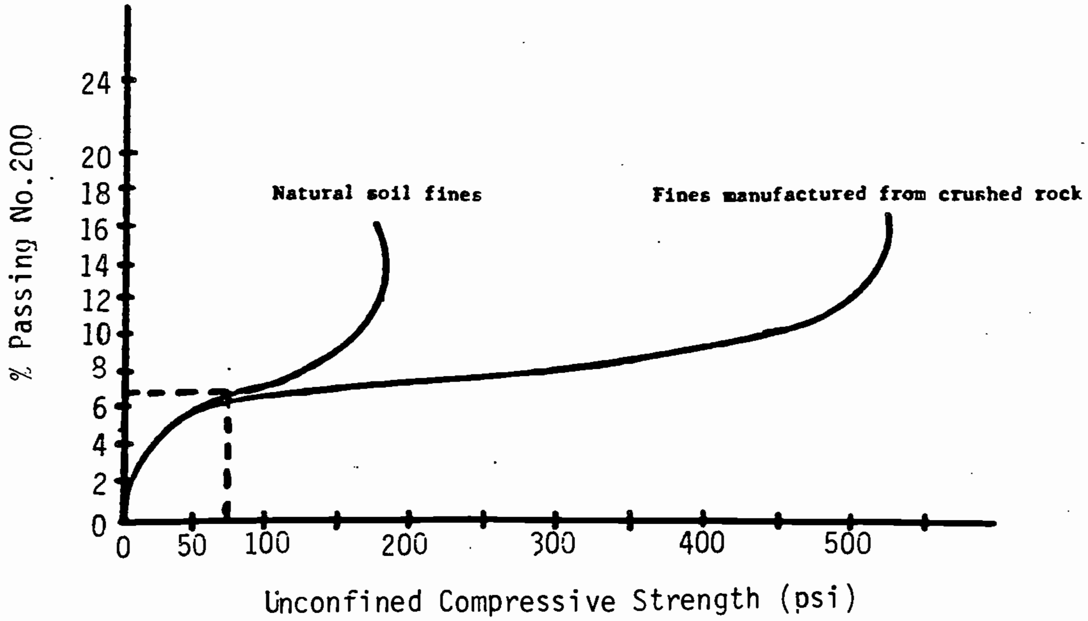

Figure 3. The effect of fine particles on crushed rock aggregate mix strength (Vischer,1979).

#200 sieve. Often when only a single aggregate mix is specified for a road, a base course mix is used. Specifying only one mixture is less costly and easier to administer than multiple mixtures. The base course gradation is specified because it drains faster and is not as likely to lose strength and stability under wet haul conditions as a surface course mixture.[4] The disadvantages of the single base course mixture are that it is more susceptible to infiltration of fine particles, rock wear and maintenance rates will be higher because there is no binder, and traction is lower than for a surface gradation. Generally, the use of a base course rock specification requires about 1.15 times the volume of rock that a surface course requires (Vischer, 1979).

For roads steeper than 16% it is desirable to haul on a tight, well bound aggregate surface. If the source rock is of marginal quality, it is not unusual to specify a larger initial size than would be desirable because the weaker rock will break down to form fine particles. In other words, after the rock has been used it will not have the same

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[4] Rock quarries in some cases have found it impractical and expensive to meet the surface course standards. Fines with PI are not normally available and the cost of adding fines can be excessive.

gradation as when it was delivered to the job site. The optimum range of fines passing the #200 sieve is between 7 and 12%.

Local experience shows that traction problems start occurring on crushed rock aggregate roads at about 16% (Pearson-Rebar,1984). More careful control of the production of the crushed rock aggregate mix, placement of the aggregate and compaction is required for rock to be used on grades greater than 16%. Vischer's experiments show that some minimum amount of binder is required in order to achieve the strength required to have a firm travel surface. The report done by Moore and Williamson (1983), outlines a number of options that might be available to increase the strength of various rock sources. This increase in strength is important at these grades because steep grades tend to produce higher load stresses on the surfacing and increases the need for binder (Moore and Williamson,1983). Experience indicates loaded log trucks climbing grades above 18% on gravel-surfaced roads, will almost always require assistance (Pearson, 1984).

Compactors are used to increase aggregate surfacing density which increases its strength. A practical upper limit for self-propelled vibrating rollers seems to be about 20%. Beyond that an assist vehicle is required for the roller increasing rocking costs (Pearson,1984).

Additional costs that might be encountered related to crushed rock aggregate surfaces if surface strength proved to be inadequate are shown in Table 1.

The costs in Table 1 are for materials only. Alternatives A and D could be done at the quarry or at the site. If addition of fines and PI material to the aggregate mix is done at the site, the cost of mixing would need to be added. The cost of mixing materials on steep roads increases with the steepness of the road due to loss in efficiency of the mixing equipment (Williamson).

There is some question as to the feasibility of rocking on road grades steeper than 20%. Some experienced engineers feel that "rocking is not a viable option due to the lower traction coefficient" on roads over 25%. A commonly held opinion is that on a 25% grade normal 1" minus or 1 1/2" minus cannot be compacted. They also observe that 9 inch to 12 inch depth of pit run will turn into a "marble-type" surface.

On roads of 25%, one suggestion has been to place a shallow depth of pit run on a road and then push it into the subgrade with a grid roller in order to strengthen the subgrade. The running surface would be covered with soil in order to maintain good traction.

Table 1. Cost of alternatives to bring to bring Yaquina Head aggregate up to 75 PSI unconfined compression strength.

A.	8% natural fines 370 PSI Dry Strength Additional Production costs $.50/ton.	357 $/mi
B.	2.5% Lime 75 PSI Wet Strength 112 $/ton x 17.8 ton/mile	1494 $/mi
C.	2.5% Cement 75 PSI DRY Strength 105 $/ton x 17.8 ton/mile	1880 $/mi
D.	Addition of binder material to increase P.I. If material hauled 100 miles to rock quarry 2-3 $/ton x 700 ton/mi	1400-2100$/mi

The cost of rocking for roads in the Oregon Coast Range is a substantial part of road cost and can be $30,000 per mile to $50,000 per mile or higher. The high cost is due to the scarcity of good quality rock and the distance the rock must be hauled. Prices for crushed rock, in place, range from $8 to $20 per cubic yard. The majority of the unit price is the cost of transporting the rock from the source to the construction site. Rock prices vary considerably with market conditions and to a lesser extent as a function of rock gradation.

Surface Drainage

General

It is estimated that as much as 25 percent of the total road construction cost is allocated to road drainage and road surface erosion protection (Lickeler and Lund, 1976).

The factors under our control are road grade and culvert spacing. Factors that are not under our control are the erosion hazard of the soil, rainfall intensity, and other hydrologic factors. The complex relationships between hydrologic factors, soil, ditch design and culvert placement have been handled in an empirical or semi-empirical manner. Local experience is commonly used. Arnold, in 1953, and Packer, in 1967, studied culvert spacing. Arnold developed a set of culvert spacing guidelines which have gained acceptance with time even though they were originally intended as preliminary guides. Arnold developed his tables from data gathered in the Douglas-fir region of the west coast. Packer's work was done in the northern Rocky Mountains. Both authors identify road grade as a significant factor in culvert spacing.

Arnold's study was done on roads with road grades of 18% or less and Packers study was done on road grades of 15% or less. As we look forward to the construction of road grades of 20% to 30% and steeper, it is important to note that the spacing guides were developed from a data set that did not include the roads with this degree of steepness.

Arnold's culvert spacing guides were derived from information about culverts that had failed and some judgment was made about what spacing would have been necessary to avoid a culvert failure. Packer's work is based on studies done on roads with no inside ditch. He measured the slope distance, grade, soil type and rainfall intensity that gave a rill depth of 1 inch. From this information, he developed a culvert spacing guide.

Both studies point to steepness of grade and length of slope as major factors in the mobilization of sediment. It is obvious that increasing road grade increases surface erosion; what is not obvious is what to do about it.

For road grades less than 16% the most common way of providing surface drainage is to use ditches on the inside of the road and drain the ditches using ditch relief culverts. Arnold's spacing guidelines are predominately used in the Douglas-fir region.

For roads that have road grades from 16% to 20%, the spacing of ditch relief culverts becomes more critical as the erosive power of water increases. Fine grained soils like those found in the Oregon Coast Range can be susceptible to erosion. Two methods which can be used to reduce erosion potential are (1) to reduce culvert spacing, and (2) line the ditches with pit run rock. Since Arnold's guides are for roads less than 18 percent, one approach to predict culvert spacing is to simply extend Arnold's guidelines by extrapolation as a rough rule of thumb. Because extending the guidelines beyond Arnold's data set involves some uncertainty, the extrapolations are often revised. Reducing the spacing by one half is not uncommon. Beschta (1984) has developed an equation from Arnold's table of culvert spacing. The equation is:

$$Y = (1777\, e^{(.0156 \bullet x)})/\text{grade} \bullet R$$

Where : Y = Culvert spacing
x = Erosion Hazard
Grade = Road Grade
R = 25-year 15-min rainfall intensity

Roads that are steeper than 20% grade are more likely to be closed when their intended use activity is over than roads on flatter road grades for safety and maintenance reasons. Because they are only used for a short period of time, there are more options available for erosion protection. If the road is constructed on a side hill, it is possible to use the road with no outslope and then blade the surfacing material against the cut bank in order to make a steep outsloped surface when the road is put to bed. A 3-4% outslope greater than the road grade is used as a minimum. Installation of water-bars is another option.

Pearson (1985) suggests that steep roads not be built with an inside ditch for long distances. This is because of the potential for ditch scour and erosion of the road bed along the ditch side of the road. With increased sediment transport ability of water at steeper gradients, culvert failure by plugging with sediment is more likely. All other options for drainage of steep roads should be looked at before concentrating water in a ditch.

Often the reason that a steep road is built in the Oregon Coast Range is to be able to stay up on a ridge top. Erosion control for ridge top roads tends to be less complicated than for sidehill roads. On ridge tops there is not the danger of a plugged culvert saturating a road prism and causing a slide. Subsurface water is not intercepted to the same degree on ridgetop roads as it is on sidehill construction. To shorten the slope distance that water travels in the ditch, it is necessary to increase the frequency of water bars. At some point, increasing the frequency of water bars becomes impractical. This can happen when the grade becomes too steep or the soil becomes too erosive. Then, something else needs to be done.

Maintenance

Introduction

Maintenance is often cited as one of the reasons steep roads are impractical. This is especially true when maintenance problems are compounded when less than ideal conditions exist in terms of weather and materials. Maintenance activities concentrate on keeping the road surface smooth and, the ditches and the culverts open. As road grade increases, both the road surface and ditch line require more maintenance.

For temporary roads that serve a small area and are being used for a portion of one season and then closed, it is possible to concentrate an intense maintenance effort in order to get through one season of haul. Short stretches of road can be maintained every day for a short period of time if necessary. Daily maintenance on grades steeper than 24% were reported on the Siuslaw National Forest for short periods of time. As a long term option, it is not practical and probably uneconomical to maintain roads daily .

In the Oregon Coast Range, because of the fine grained soils (AASTHO) and plentiful rainfall, it has been necessary to surface most roads that are intended to be kept open. The maintenance of these surfaces on steep roads is a problem. When graders are used to maintain a crushed rock surface, the surface is bladed up, reblended, and spread back out over the road. Layer thickness theory suggests that the ideal depth of rock aggregate that needs to be reblended is two times the diameter of the largest particle in the surface (Williamson, 1984). The equipment used to maintain the roads often cannot work with that amount of material. Surfacing is reblended in place with a four-step process. First, the loose large diameter pieces on the surface are swept to one side and windrowed with the grader blade. Second, a depth of the running surface is bladed off into another windrow. Usually the depth that is bladed up is 2 inches or less (Fulton, 1984). Next, both windrows are mixed together using the grader blade in order to get a uniform mixing of the particles. Finally, this mix is spread out over the road surface. Generally, the only compaction this surface receives is from subsequent use by vehicles. This process becomes difficult if maximum particle size is larger than 1 1/2 inches (Fulton, 1984). Vischer (1979) points out that "another point for consideration for aggregate surface roads is that if a dense graded surface aggregate with adequate binder is used, over one without binder, the rock wear rate and maintenance rate will be less for the one with binder."

How important this consideration is depends on the traffic level and the added maintenance costs incurred at that level of use. Road surfacing design and materials and level of use dictate road maintenance costs. Low anticipated traffic volumes dictate low design standards for road construction and low road maintenance levels. Neither construction costs nor maintenance costs can be looked at separately in deciding to what standard to build the road. Predicting the performance of a design in terms of maintenance costs and servicability is where the experience of the design engineer is essential. Vischer estimates that "if the specification restrictions were even more restrictive on the aggregate surface course or stabilizers were added, the maintenance costs and surface rock replacement costs for maintenance levels III and IV could be reduced by at least 1/2 and in some cases probably 2/3". He also reports that dust abatement maintenance could be reduced if stabilizers were added to the crushed rock aggregate.

Rock gradations that have performed well.

Vischer (1979) has suggested a surface rock specification that could cut maintenance cost by half. Vischer developed the information for this gradation through field observations and laboratory testing. Tests were performed on the samples in order to determine their unconfined compressive strength. The results of the field observation and the laboratory testing identified some properties that were common to the samples and were deemed necessary for acceptable performance in surface course aggregates. He suggests a plasticity index of 9 or less and that the average unconfined compressive strength of 3 test specimens be greater that 75 psi.

Ames (1984) identified rock gradations that have performed acceptably from the standpoint of maintenance and traction on roads with grades from 14 to 20%. The composite set of gradations that has come from his work forms a band that is slightly wider than Vischer's band of acceptable gradations (see Figure 4).

Table 2. Comparing Ames gradation with Vischer's recommended Gradation

Sieve Size	% Passing Ames	Vischer
3"	100	---
1"	71-100	100
.75"	64-96	---
.5"	53-88	68-80
.375"	48-80	---
#4	35-64	42-54
#10	19-49	26-38
#20	10-38	---
#40	8-30	12-23
#100	6-21	---
#200	4-16	7-12

Both are based on aggregate mixes that have performed well in use and have common observed attributes such as good traction and low maintenance. The work done on the Willamette (Vischer, 1979) and to a certain extent the work done by Ames (1984) on the Okanogan, was on rock that was

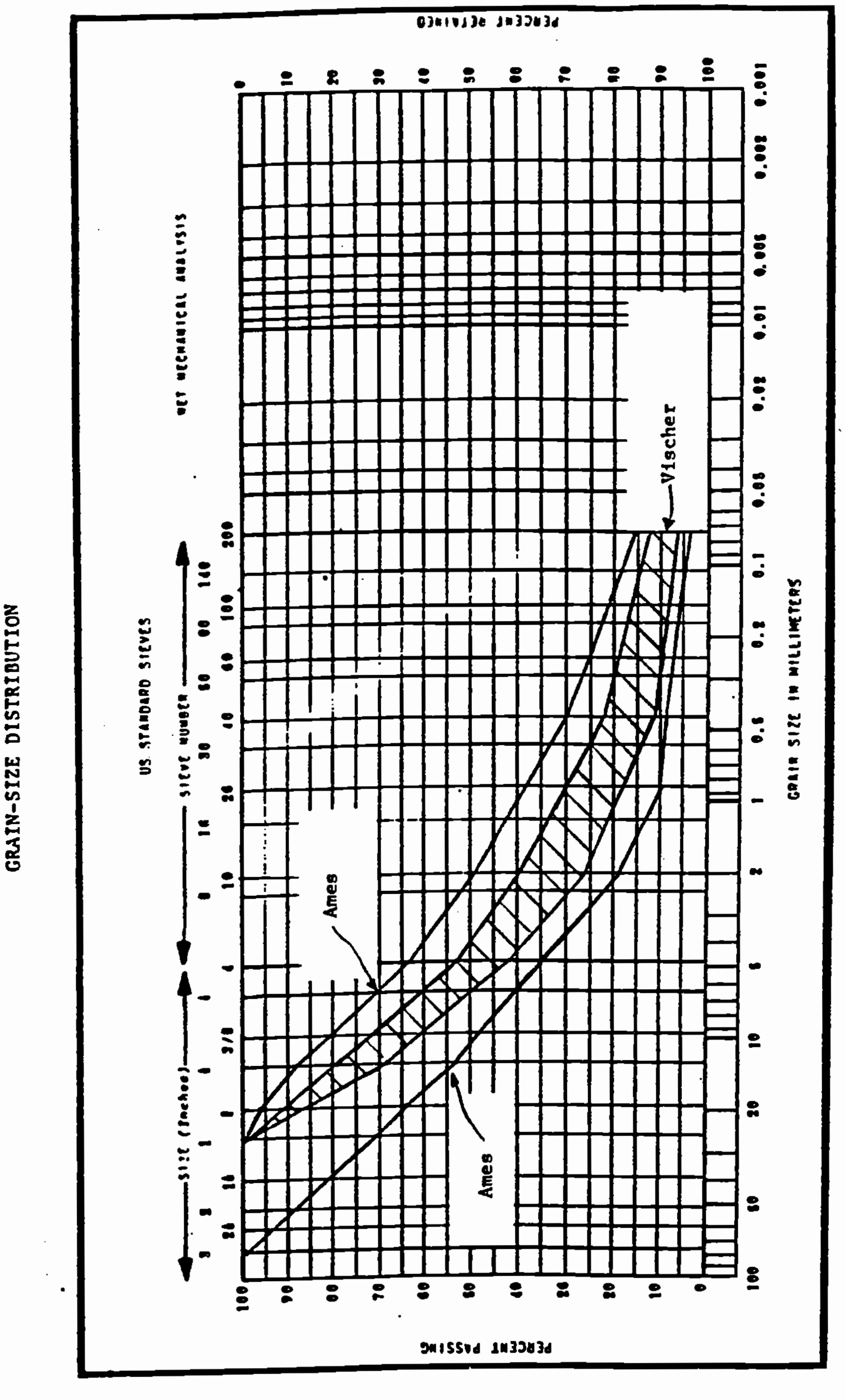

Figure 4. Comparision of Vischer's recommended crushed rock gradation with Ames's gradation.

fairly hard and durable. To effectively transfer that information to the generally poorer quality rock of the Coast Range, will require further research.

Maintenance on roads 16-20%

As road grades become steeper than 16%, maintenance becomes more difficult. Water trucks and graders become less efficient. Managers who were contacted were generally in agreement that maintenance costs "really take a jump" when roads are steeper than 16%. None of the people interviewed were able to quantify this "jump" other than to say a substantial increase. The maintenance cost on these roads has been higher but apparently not high enough to outweigh the advantages that are associated with building steep roads.

Some managers have reduced the maximum particle size that they specify in their aggregate mixes from 1 1/2" to 1" or even 3/4" to facilitate mixing by grader (Negier, 1985).

Another road grade related maintenance problem occurs when maintenance crews try to clear small slumps that are blocking a drainage ditch. The front end loaders used to move the material can become unstable when used on steep grades.

Maintenance on roads 20%+

Roads that are constructed at grades greater than 20% are generally not intended to be kept open and are usually single use roads. They are intended to access a limited area, serve their function, and be closed. As a result, the general consensus among engineers is that roads over 20% grade have not had any extraordinary long-term maintenance problems.

Temporary roads with grades over 20% are where extraordinary short term maintenance efforts can occur. Maintenance efforts on an unsurfaced roads may include watering, grading and compacting the road on a daily basis. On a crushed rock aggregate road, they may include adding binder to the road surface. This maintenance is usually performed in an effort to avoid having to assist log trucks out on adverse grades.

In one instance, the contractor watered, graded, and compacted the unsurfaced road every night to enable unassisted log haul on a 26% adverse grade. In another case, a contractor added fine crushed rock material to a crushed rock aggregate road in order to improve traction. The road grade was 24% with pitches of 26%. The operator was unable to improve traction enough to allow the trucks to handle the adverse sections of this spur road unassisted. The treatments and conditions of use are so varied that our ability to predict when these treatments will work is limited. This is another area for further research.

Haul

Gradeability

A major consideration in steep road operation is vehicle gradeability. Gradeability is defined here as the maximum grade that a vehicle or vehicle combination can climb. Surface composition, density and geometry are important in the discussion of steep roads because they strongly affect gradeability. Surface maintenance such as watering and additives to surfacing are designed to increase gradeability. This section will assume the most important vehicle is the log truck due to its frequency and the intended use of the road. Common log truck specifications for haul on steep roads are typically 6 x 4 on-highway trucks with overall gear reductions of 80:1 to 130:1 and engines that generate from 300 hp to 475 hp, and are not generally power limited (Stryker, 1977).

There are a number of formulas to predict log truck gradeability including those by Stryker (1977), McNalley (1975), Western Highway Association (1976), and Sessions (1984). The formulas differ in the level of detail required, with the formulas by Stryker and Sessions being the most complete. The differences between Sessions' and Stryker's are that Sessions' does not use the assumption that the normal force on the tractor rear axles is equal to the normal force on the trailer axles and includes rolling resistance. The gradeability equations and derivations are in Appendix IV. The most important variable, coefficient of traction, is included in all formulas. Unfortunately, although the coefficient of traction is the most important gradeability variable, there does not appear to be a reliable method of predicting coefficient of traction, nor a simple field method of measuring coefficient of traction. An approach to this problem is outlined in the section on laboratory testing.

Using coefficients for firm earth of 0.55 (Caterpillar, 1983) and 0.65 for dry earth (Taborek, 1957) maximum loaded log truck gradeability changed from approximately 24% to 29%. On crushed rock surfaces, traction problems begin appearing at 18%--depending upon the quality and gradation of the rock and the condition and geometry of the road (Pearson, 1984). On roads steeper than 16%, the Siuslaw National Forest usually includes the cost of log truck assists in their timber sale appraisals.

Assists

When traction is not sufficient, an assist vehicle can be added. For the purpose of this analysis, it is assumed that the assist vehicle and the vehicle being assisted can work together to produce the maximum thrust available from both vehicles. The basis of this assumption is that tractors reach their maximum thrust at relatively low slips and maintain this thrust over a wide range of slip (Wong, 1982). Since the maximum thrust can be achieved over a range of slips, the assist combination adjusts its speed until both vehicles achieve maximum thrust or the necessary thrust. Common assist vehicles in the Northwest include crawler tractors and rubber tired skidders.

Consider a loaded log truck weighing 70000 lbs being assisted up an adverse grade. From Figure 5, the additional thrust required from an assist vehicle is plotted against grade. The downward sloping lines represent the thrust that could be developed by an assist vehicle weighing 56000 lbs. For this example, the gradeability for the log truck and assist vehicle combination would be 37.5% . Practical limits under good conditions for log trucks with tractor assist appear to be in the 30% to 40% range for adverse haul.

Occasionally it is necessary to move unpowered vehicles up adverse grades. Figure 6 estimates the assist required to move an unpowered vehicle up various grades and the ability of the assist vehicles to develop thrust for a given normal force and coefficient of traction.

For this example, the vehicle being assisted has a rolling resistance of 3% of the normal component of vehicle weight. The assist vehicle is assumed to weigh 56,000 lbs and has a coefficient of traction of 0.65.

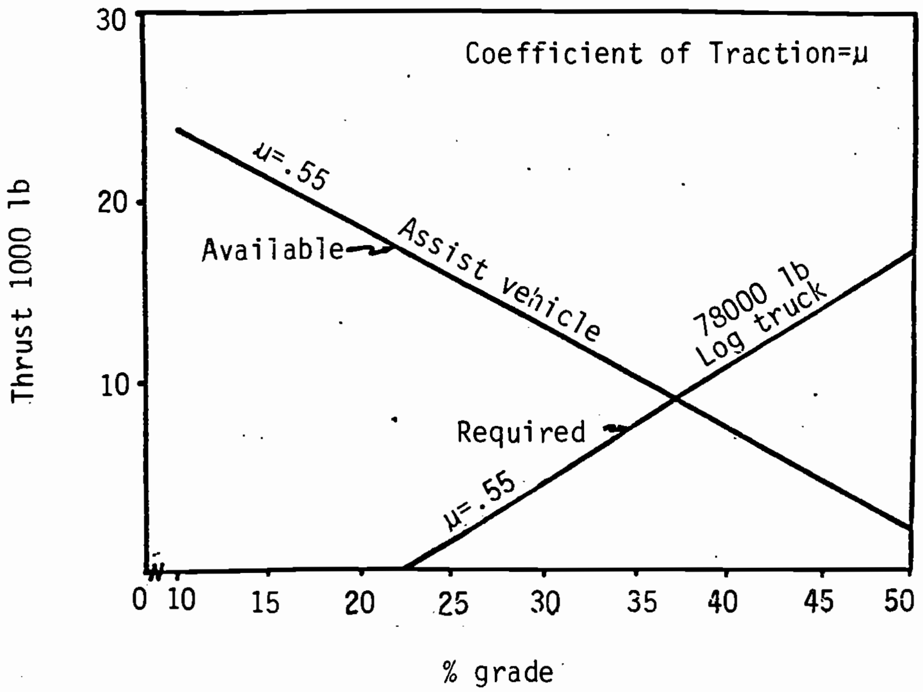

Figure 5. Thrust available from an assist vehicle and thrust required by a loaded log truck on various grades.

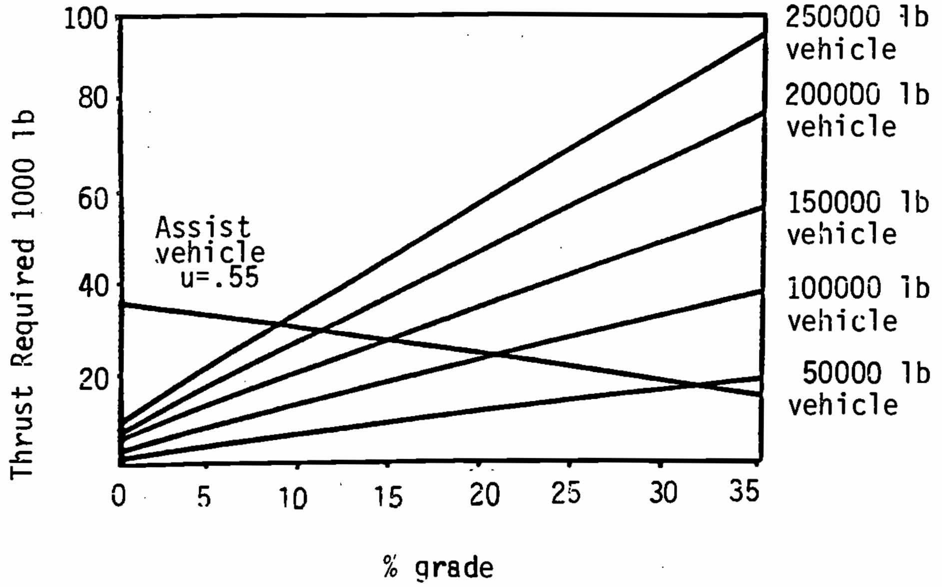

Figure 6. Thrust required to move an unpowered vehicle up adverse grades.

Various vehicle weights are plotted for required thrust versus grade. The point where the downward sloping line of the assist vehicle intersects the line for a particular vehicle weight is where the combination of dead weight and assist vehicle would be traction limited. For example, to move an unpowered 150,000 lb vehicle up a 20% grade, you would need an assist from a crawler tractor larger than 56,000 lbs.

Multiple assist vehicles can be also used. When situations require more thrust than one assist vehicle can provide, tractors have been hooked together to provide the needed assist.

A gradeability model for a log truck and tractor assist vehicle can be constructed to estimate the theoretical maximum gradeability of the combination. Sessions' gradeability model was modified to add the effect of a tractor pushing a loaded log truck up an adverse grade. The tractor assists the log truck by pushing on the back of the load. The model takes into account the different coefficients of traction for the tractor and the log truck drive wheels. The model is derived in Appendix IV.

Curvature

A vehicle negotiating a curve while climbing a grade must develop more thrust for two reasons. First, when a rolling tire is made to change directions, as in cornering, a drag force is produced. The total thrust required is the

vector sum of the tangential forces (including drag) and the lateral force to oppose centrifugal forces. Second, as a vehicle travels around a curve, the vehicle follows a path that puts it on an incline that is steeper than the centerline grade of the road. Thus, the vehicle "sees" a steeper grade than the centerline grade of the road. This increased grade applies to assist vehicle combinations as well as unassisted vehicles. The effects of curvature on log truck gradeability are discussed by Stryker (1977). For zero superelevation, Stryker reports the actual grade can exceed the centerline grade by as much as 3 percent depending upon the radius. Similarly, tracked vehicles also encounter increased resistances due to turning.

When calculating maximum gradeability, the effects of curvature should be taken into account. For purposes of comparison, all calculations in this paper assume straight road sections.

Gradeability improvements

Gradeability can be improved by increasing the weight on the drivers, increasing the number of driving wheels, or increasing the coefficient of traction.

In some situations, it might be possible to load the front bunks more heavily or to load the rear bunks less heavily. This option would depend upon vehicle axle ratings and axle limits along the truck route.

Another option would be to add front wheel drive. For on-highway trucks, the additional investment for front wheel drive is approximately $10,000. Figure 7 shows the increase in gradeability gained by adding power to the front wheels. In the ranges of coefficient of traction between 0.4 and 0.6, powering the front wheels adds 4.0% to 4.5% gradeability. Log trucks with 6 x 6 power trains are not common in the Oregon Coast Range due to higher initial cost and maintenance cost.

The coefficient of traction can be affected by using tire chains and reducing tire pressure. The Western Highway Institute (1976) performed traction tests that included evaluating the effect of sanding snow covered roads and the increase in traction with the use of chains. They found that either chains and/or sanding on packed snow increased the the coefficient of traction from 0.25 to 0.33, but together no significant additional benefit was derived. Gill (1967) measured improvement in traction on soil when traction improving devices are added to rubber tires. He found that at maximum pull traction performance was improved from 0% on loose dry sandy loam to 17% on medium loam with a frozen crust. At 15% slip, traction performance varied from -8% on loose dry sandy loam to 9% on medium loam.

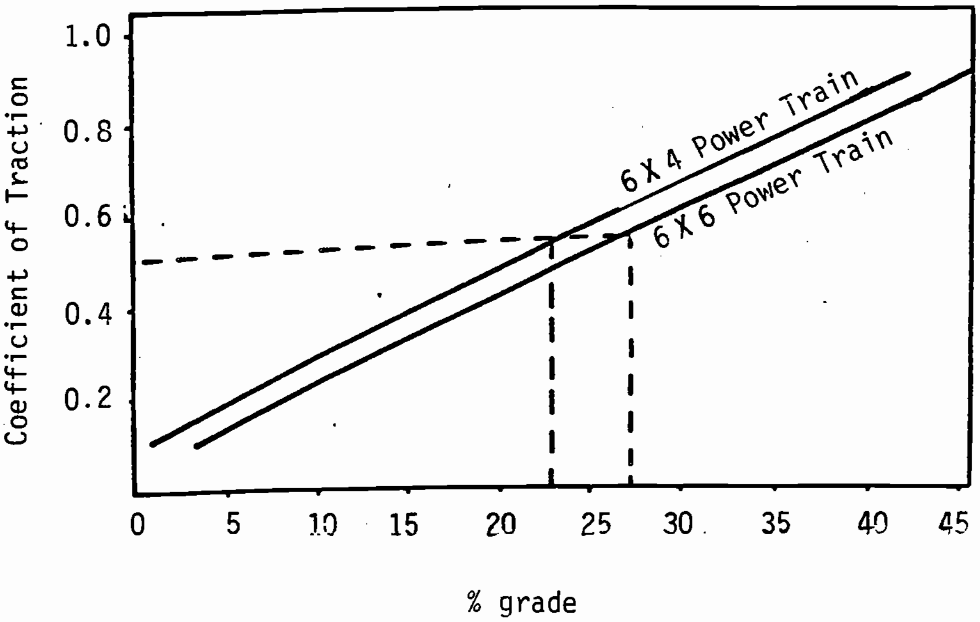

Figure 7. The increased gradeability that could be expected due to powering the steering wheels.

From the results of these studies, it appears that an increase in traction can be achieved by using chains under some conditions. However, the use of chains may make the maintenance of a firm, smooth surface more difficult and possibly affect multiple vehicle passage. No literature on log truck performance with chains on soil or gravel surfaces could be found.

Military vehicles have used low pressure to increase mobility for some time. Wismer and Luth (1973) correlate wheel thrust with tire contact area. Reducing tire pressure increases contact area, as well as rapidly reducing tire life (Fitch, 1976). No documentation could be found on the coefficient of traction as a function of air pressure for log trucks.

Downhill Gradeability

Steep favorable road grades present a different kind of gradeability problem for trucks. Uphill gradeability requires the drive wheels to develop as high a coefficient of traction as possible. Tire slip is increased until the maximum coefficient of traction is reached. Slip is not necessarily a safety hazard. For downhill travel, tire slip is more critical. Usually, the maximum coefficient of traction is achieved at about 15% to 20% slip. Since slip would occur on all the wheels that are being braked, slip is usually kept below the point where the maximum coefficient of traction can be obtained to maintain control of the vehicle.

Figure 8 is a typical coefficient of traction versus slip curve. The problem in designing to the maximum coefficient of traction is twofold. First, in downhill gradeability it is not only the drive wheels that slip; all wheels that are equipped with brakes will slip. If the peak of the coefficient of traction curve is exceeded and too much slip is developed, it is likely the wheels will lock up and control be impaired or lost.

Engine Brakes - Prior to World War II, brakes on log trucks were less reliable and loss of control on down grades was much more common than it is today. In the 1920s, log trucks with solid wheels operated on plank roads with favorable grades as steep as 30%. Vacuum brakes on log trucks came into use around 1920; compressed air brakes appeared in the early 1940s (Wentz, 1983). After World War II, a reduction in maximum road grades was seen. In the 1960s and 1970s, as a result of improved braking systems and reduced road grades, loss of control of log trucks due to brake failure was less common than before World War II.

A major improvement in log truck braking has been the Jacobs engine brake, developed in the early 1960s by Clessie and Lyle Cummins (Wentz, 1983). Since that time, Jacobs engine brakes have become the industry standard. Other

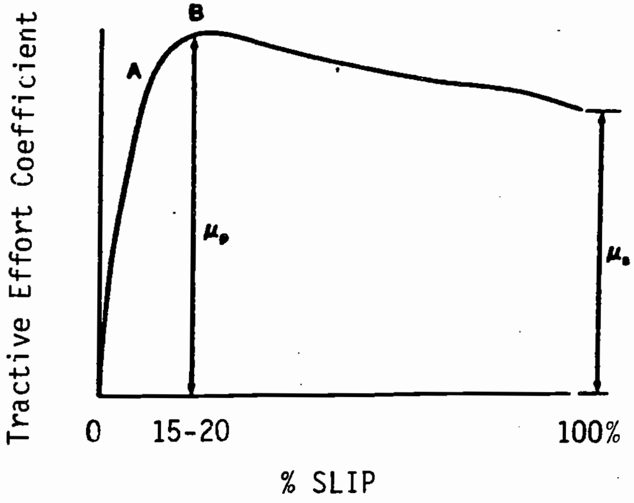

Figure 8. Typical coefficient of traction curve as a function of slip. (Wong, 1978)

retarding systems are available to assist in braking tractors, but the Jacobs engine brake is the most common in West Coast logging. The maximum braking horsepower developed by an engine and Jacobs brake combination is dependent on displacement, compression and injection timing of the engine, the model of Jacobs brake used, and engine speed (Olsen, 1985). Power dissipation capability can exceed 100% of the horsepower rating. Currently, the larger displacement engines with lower compression ratios may produce less braking horsepower than smaller displacement engines with high compression ratios. See Appendix V for a typical specification sheet. Energy dissipation is controlled by controlling engine speed and on some models by reducing the number of cylinders used for braking.

Service Brakes - As road grades become steeper, the amount of energy the brakes must dissipate increases. For example, an 80,000 lb log truck traveling at 10 mph equipped with a Jake brake capable of producing 285 braking horsepower descending a 10 percent grade does not require the assistance of service brakes. At 15% grade the service brakes must handle 10% of the braking load, at 25% grade the service brakes must handle 45% of the braking, or 231 horsepower.

The percentage of braking that each axle does may not be proportional to the static axle load. In order to determine if braking is going to be a problem, it is necessary to determine how much work each axle is doing. Kenworth and Rockwell tested brake performance on tractor trailer combinations to determine the amount of braking each axle does. The tractor trailer combination tested was a Kenworth C.O.E. tractor and a Frauhauf refrigerator trailer. The front axle was equipped with 15" x 4" brakes and the tandem axles were equipped with 16.5" x 7" brakes. The tractor tandems were equipped with Rockwell axles with "Q" brakes and Abex 551-C "low friction" brake lining. (Test Report, 1983).

The results of this testing showed that the tractor tandem does about 52% of the braking and carries 44% of the static load. The trailer tandem does about 41% of the braking and carries 44% of the static load. The front axle did about 7% of the braking and carried about 12% of the static load.

From the standpoint of braking, the tractor-trailer combination that was tested would be equivalent to a loaded log truck (Taylor, 1985). The tractor tandem absorbs a higher percentage of the energy used to stop the loaded vehicle. According to the test data, the tractor tandem would be expected to heat up to a critical temperature first. Truck brakes begin to show substantial fade at about 650°F (Taylor, 1985). The normal operating temperature for brakes is somewhere around 200°F so a critical temperature rise would be about 450°F.

Temperature Rise - There are two approaches to brake drum heating: (1) calculating average temperature rise of the whole brake drum (Taborek, 1957) and (2) calculating the temperature rise at the interface between the brake shoe and drum (Newcomb and Spurr, 1967).

Taborek finds the temperature rise Δt as a result of heat input from the kinetic energy dissipated during braking. The equation is:

$$t = \frac{Hp\ in}{23200(C)(Wdr)}$$

where: Hp in = Horse power dissipated by a particular brake drum

C = specific heat of the brake drum

Wdr = weight of drum

The result gives the average temperature rise for the entire drum. Newcomb and Spurr (1967) call this the uniform bulk temperature increase of the drum. This temperature is less than the temperature that could be expected at the point of contact between the brake shoe and the brake drum.

The Newcomb and Spurr equations represent the temperature rise at the point of contact between the brake shoe and the brake drum as the vehicle travels down a gradient and the brake is steadily applied to maintain a constant speed.

The equations are:

$$T = \frac{2a^{.5}\ t^{.5}\ N}{k\ 3.1416^{.5}} \qquad \text{when } L>1.21$$

or

$$T = \frac{a\ N}{k\ d}\ (t + d/3a) \qquad \text{when } L<1.21$$

where

$$L = d/(a\ t)^{.5}$$

Where: T = Temperature rise in °C
t = time of stop (sec)
N = energy input to brake drum (ft-lb/sec)
k = thermal conductivity (Chu/ft sec °C)
a = $k/p.c$
p = density (lb/ft^{3})
d = thickness of brake drum (ft)
c = specific heat (Chu/lb °C)

Newcomb and Spurr (1967) point out that these equations do not account for cooling and, "If the time of descent is long, cooling loses from the exterior of the drum surface must be considered."

Figure 9 shows the amount of energy that must be dissipated at a given speed and grade. The wheel brakes must dissipate the amount of energy that the engine brake cannot dissipate. Figure 10 represents temperature rise in the tractor tandem brakes for different levels of work done by the brakes.

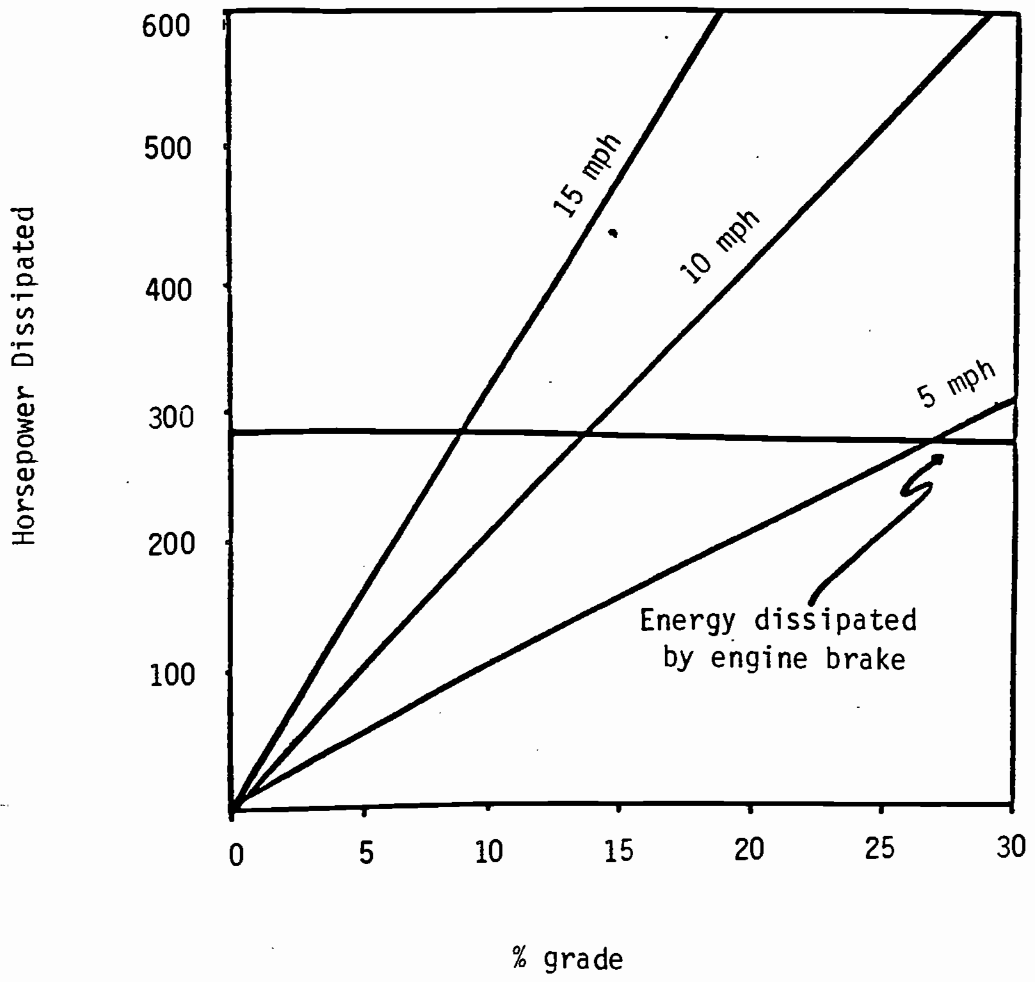

Figure 9. Horsepower that must be dissipated as a loaded log truck decends various grades.

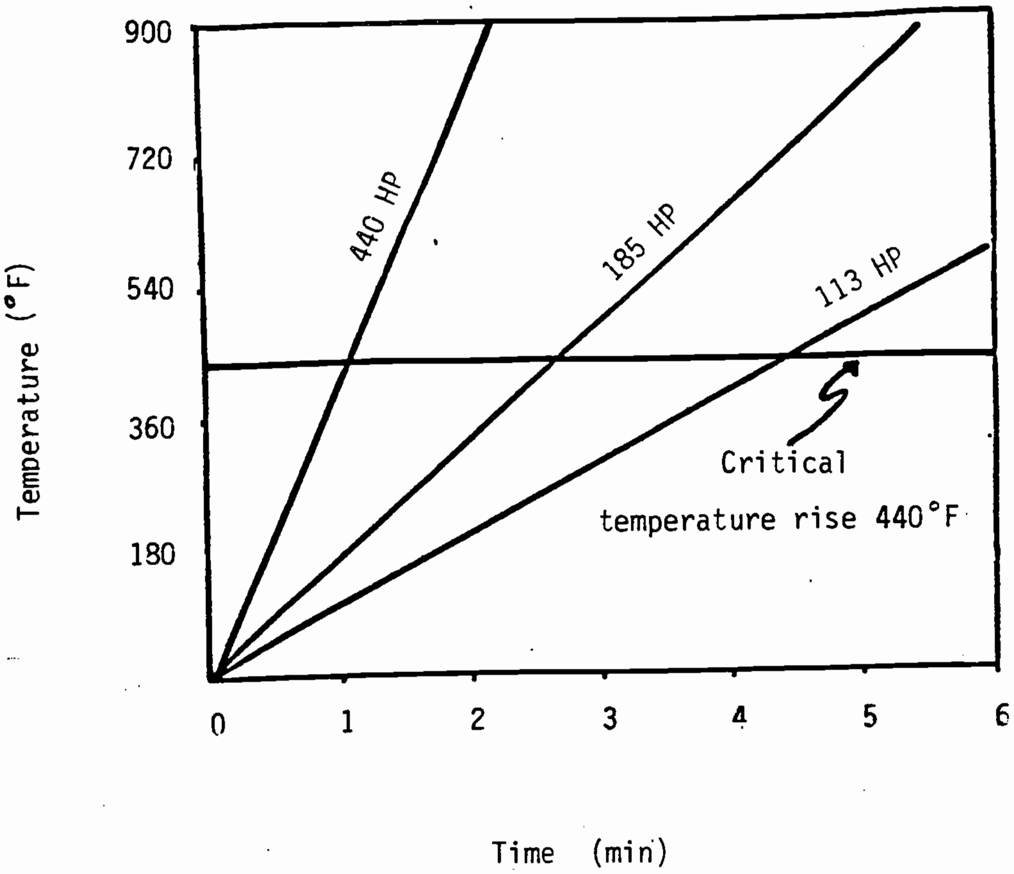

Figure 10. Temperature rise in the tractor tandem brakes as a function of energy dissipated by the total service braking system.

Some log truck trailers have been equipped with ten inch wide brakes with the objective of distributing more of the braking load to the trailer brakes. Ten inch wide trailer brakes have not been widely accepted due to higher initial cost and reportedly increased maintenance problems (Taylor Motors, 1985).

Other retarders - There are other retarding devices available. They include the Hydrotarder which uses water as a medium to absorb heat energy. A pump controlled by a valve in the cab forces water into the retarder to act on its impeller, the retarding force developed is dependant upon the amount of water forced in.

The oil operated retarder works on the same principle as the Hydrotarder. The only difference is that it uses oil instead of water. A third device is the electro magnetic retarder. This device is a generator that draws power from the driveline and helps brake the truck. All three devices mentioned above are heavy, cumbersome and costly (McNally, 1975).

Exhaust brakes are available to act as retarders. They restrict the flow of exhaust gases and provide retarding force when the exhaust brake is closed. Their efficiency depends on exhaust manifold pressure (Thompson, 1962).

Traction Limited Case - Traction limiting grade is found by setting the resisting forces equal to the sliding forces to find the grade at which they are equal. Assuming braking effort is proportional to the dynamic axle loadings, this is equivalent to saying that the maximum downhill gradeability is equal to the coefficient of traction in percent.

Wong (1978) references a braking effort coefficient of about 0.40 for bias ply tires (Figure 11). In a study relating tire wear to slip, coefficients of friction were developed by Della-Moretta (1974). This study found that for cases where tire slip is less than 15% the coefficient of traction for sand and gravel aggregate surfaces was less than 0.50 (Figure 12).

Sliding coefficients of traction resulting from wheel lockup are lower. Since braking effort may not be in proportion to dynamic axle loadings, the sliding coefficient of friction might provide a more conservative estimate due to possible lockup of one or more axles. Just as trucks are traction limited on adverse grades, trucks can also be traction limited on downhill grades. On steep downhill grades, the full energy dissipation capability of the engine brake may not be usable. Instead, the output of the Jake brake must be reduced by reducing engine speed, using a reduced setting on the Jake brake, or relying only on the service brakes. The objective would be to divide the braking load among all wheels in proportion to the normal loads in order to develop the maximum braking thrust.

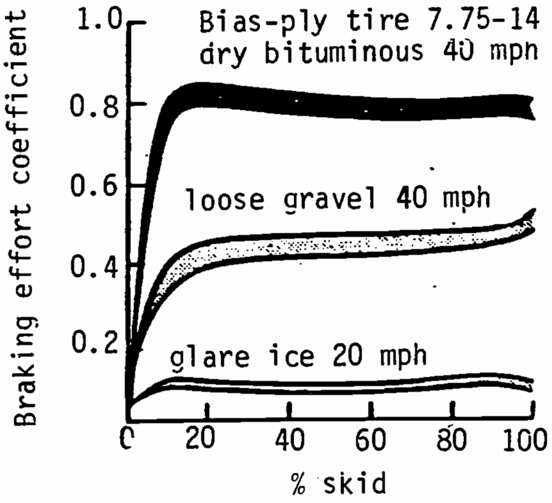

Figure 11. Coefficient of traction as a function of surface type and percent slip. (Wong, 1978)

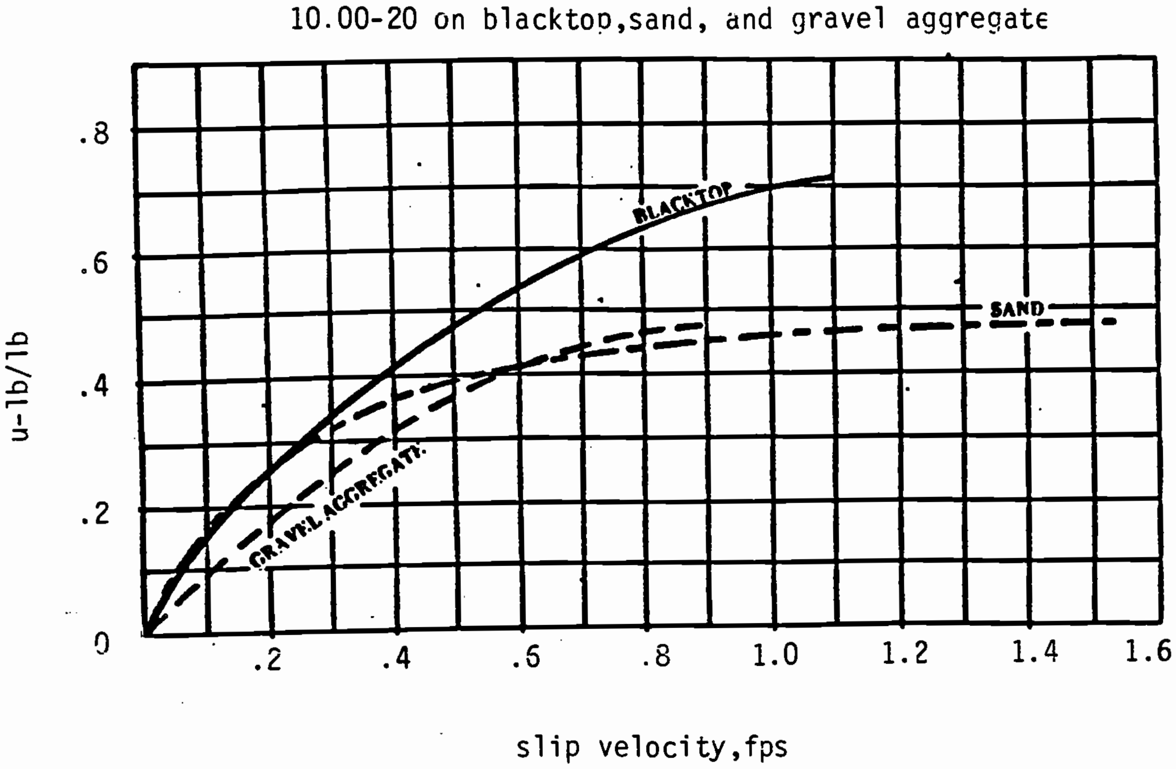

Figure 12. Coefficient of traction developed as a function of slip. (Della-Moretta, 1974)

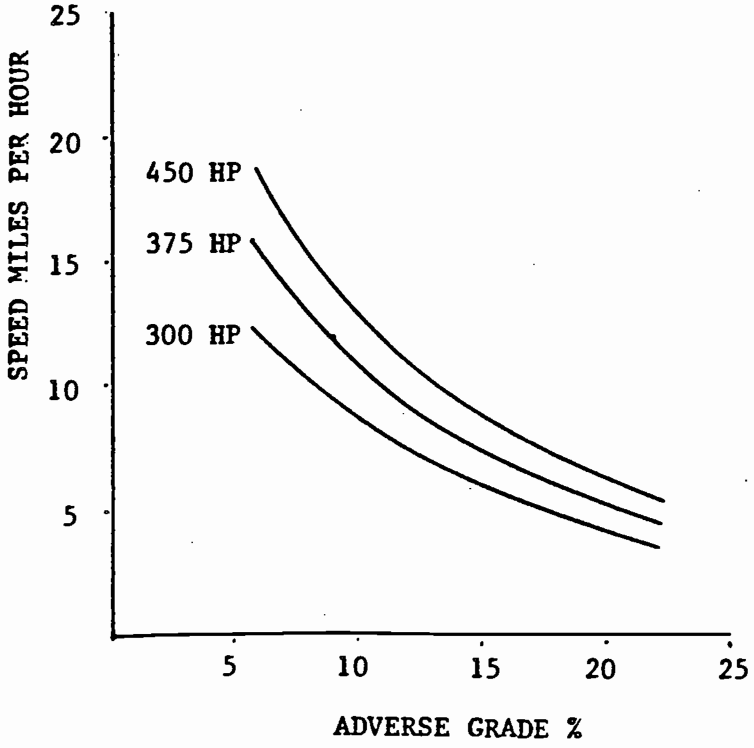

Figure 13. Horsepower limited speed on adverse grades including the effect of slip.

Rickard (1984), summarizing interviews with local contractors and private timber companies in western Oregon, reported that loaded trucks were able to descend, assisted, down favorable grades of 25%. One contractor had hauled on 34% favorable grade with the loaded trucks assisted down with a tractor.

Haul Costs

There are several approaches to calculating haul costs, all of which involve estimating the round trip travel time. Three approaches discussed here include empirical, semi-empirical, and analytical. The empirical method consists of measuring truck times over the actual route or a regression analysis of truck times over similar routes. The semi-empirical method combines empirical observations with some theory, while the analytical method uses principles of mechanics to determine truck performance. The empirical method and semi-empirical methods appear to be the most widely used methods in the Coast Range.

The empirical method, as described above, uses measurements of actual truck trips over similar roads as an estimate of the travel time over proposed roads. One example of the empirical method is the speed-grade relationship developed by Byrne, Nelson, and Googins (1957) for favorable grades not controlled by alignment.

The most widely used semi-empirical method for estimating truck travel time as a function of grade and alignment also uses the results of Byrne et al. (1957) to combine empirical derived alignment models with analytical gradeability models.

I could not find any use of analytical models being used to estimate log truck travel time on forest roads, although at least one has been developed. (Vehicle Operating Cost Model, Della-Moretta, 1975). Analytical models such as the Vehicle Mission Simulator developed by Cummins (McNally, 1975) are used by industry for estimating truck performance for interstate travel.

For steep adverse grades where alignment does not control and truck speed can be estimated by principles of mechanics, McNally (1975) suggests the following formula for power limited speed as:

$$MPH = (NHP \times E \times 375)/(RR + GR + AR)$$

Where: AR = air resistance and can be ignored for speeds less than 30 MPH

NHP = horsepower

E = drivetrain efficiency

RR = rolling resistance

GR = grade resistance

For grades requiring development of large thrusts, McNally's equation should be modified to include tire slip as follows:

$$MPH = (NHP \times E \times 375 \times (1-Slip)) / (RR + GR + AR)$$

Della-Moretta (1975) found that tire slip was a function of the coefficient of traction generated. If the coefficient of traction is known, then gradeability can be calculated using the gradeability formula described in this report Appendix IV.

Table 3 relates slip developed to coefficient of traction and percent gradeability for gravel aggregate.

Table 3. Relationships between coefficient of traction and grade.

Coeff. of traction	slip %	Grade %
.1	1.4	1.33
.2	3.15	5.82
.3	5.48	10.50
.4	8.20	16.55
.45	10.96	17.81
.55	20.00	22.94

Figure 13 shows the horsepower limited speed of a typical loaded log truck on gravel aggregate including the effects of slip. It can be seen that for grades steeper than 15% a loaded truck with 450 hp will be limited to a speed less than 9 mph.

Byrne et al., (1957) measured truck speeds on favorable grades where sight distances were not a controlling factor. They found that downhill speed (mph) = $2.4 /(.03-G)$ where G is road grade as a negative decimal percent. The plot of their data is shown in Figure 14.

There is only one data point for road grades steeper than 12% and care should be applied in extending results beyond the range of the data. For example, a road grade of 20 percent would have a driver descending the grade at 10 miles per hour. From the previous discussion on braking, the implications of descending a grade at this speed are that the tractor tandem brakes would achieve a temperature rise of about 360°F per minute. This temperature rise was calculated assuming that trucks did not have engine brakes.

Hauling cost is derived from dividing travel time by truck cost per minute. A current estimate of truck cost for logging trucks in the Coast Range is about $1.00 per minute (Devine, 1985).

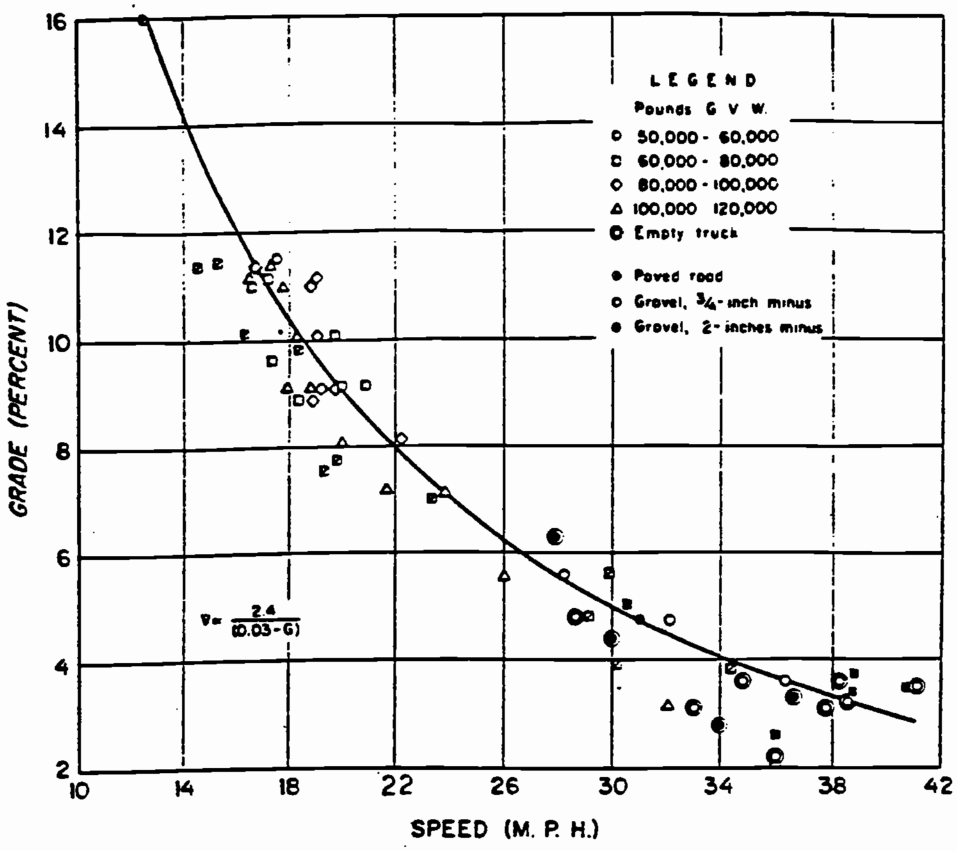

Figure 14. Speed of log trucks on various favorable grades.
(Byrne,1960)

IV. SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH

Current practices for construction and operation of steep roads in the Oregon Coast Range have been summarized based upon a literature review and interviews with knowledgeable sources. A limited amount of field and laboratory testing was done to gain further insight into conditions in the road surface during log haul. The factors that were affected by grade were clearing and grubbing, excavation, surfacing, drainage, haul, and maintenance. The technical and cost relationships between road grade, construction and operation have been identified. The limited information available suggests that substantial future research is needed to clarify both technical and cost relationships between road components and grade for steep roads. The following areas are recommended for future research:

Excavation

The cost of excavation is the product of excavation volume and cost per unit volume. Steep roads obviously reduce excavation volumes by both shortening climbing roads and permitting ridge top roads. However, the literature did not identify a relationship between unit costs and road grade. Engineers and contractors interviewed were unable to identify any increase in cost per cubic yard of excavation with increased road grade. Engineers estimated that it either did not increase as a function of grade or increased less than 10% for a grade increase from 15% to 20%.

To test the hypothesis that the unit cost of excavation is a function of road grade will require time studies on road excavation.

Rocking

There is not a consensus among engineers about whether the gradation of the crushed rock aggregate that is on the surface should be fine or coarse. Densely graded fine aggregate (3/4" minus) has the advantages of superior traction and maintenance characteristics. Open graded 1.5" minus to 2" minus crushed rock aggregates provide better wet weather support than the 3/4" minus if the 3/4" minus material is not supported by a base course. In cases where open graded material was advocated, wet weather haul was invariably mentioned as a concern.

Research needs to be done to evaluate the traction characteristics of various crushed rock aggregate mixes as function of road grade. A simple field method needs to be developed to predict in-place coefficient of traction.

Surface Drainage

Arnold's culvert spacing guidelines are still used as the basis for culvert spacing in the Pacific Northwest. These guidelines were derived for road gradients less than 18 percent. Further research should be done to validate Arnold's guidelines for use on road grades steeper than 18% and to evaluate ditchline erosion as a function of road grade and culvert spacing.

Road Maintenance

Design engineers, contractors and maintenance supervisors agree that maintenance costs increase as road grade increases. The literature did not include any guidelines for road maintenance as a function of road grade and none of the sources interviewed could provide any quantitative estimates of maintenance cost as a function of grade. Research needs to be done to determine the operating characteristics and efficiency of road equipment for road surface and ditch maintenance on steep roads. Research also needs to be done to determine the frequency of road maintenance activities for steep roads as a function of grade, traffic, surface, and drainage.

Gradeability

Gradeability models which have been developed to model modern stinger-steered log trucks are based upon the front bunk acting as the fifth wheel for a tractor-trailer combination. For very steep grades, the reach may need to be coupled to the stinger to prevent the logs slipping through the bunks. The coefficient of log-to-bunk friction and log-to-log friction has not been identified and the dynamic weight distribution assumptions may need to be modified for grades over 30 percent.

There is no consensus on what the coefficient of traction is for a given soil at a given density and moisture content. An approach to this problem is outlined in Appendix II on laboratory testing.

Haul Costs

Haul costs can be calculated if the round trip travel time for the truck is known. Byrnes et al. (1960) completed a study of truck travel times and hauling costs based upon on truck performance studies in 1947 and 1957 price data. The study was done before turbochargers and engine brakes became standard equipment on log trucks and when road grades were not being built on as steep a grade as some current roads.

Truck performance on steep grades needs to be measured to determine current technical relationships between truck performance, road grade, alignment, and driver reactions.

There is no documentation on the effect of road grade and road surface type on truck maintenance. A study of truck maintenance records will be necessary to determine the level of cost increase.

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Personal Communications

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Neiger, A. Engineer, Eugene District

Private Companies

Olsen, C. Engineer, Cummins Engines

Taylor, B. Engineer, Kenworth Trucks

Various- Taylor Motors

APPENDICES

APPENDIX I

Field Testing of Road Surfaces

FIELD TESTING

General

The soils in the Oregon Coast Range are derived from sandstones, siltstones, and mud stones. The soils are characterized by a very fine texture ranging from 35% to 95% passing the #200 sieve. Typically, these soils have low plasticity (P.I. less than 10) and California Bearing Ratios of 12 or less. Basically the soils are fine grained and do not have a great deal of strength when they are wet. Soils were described in the report were classified using the AASHTO soil classification system.

Field Testing

In an effort to better quantify the properties of roads built on steep grades, density and moisture content tests were conducted. An unsurfaced road and a crushed rock aggregate road were each tested on two occasions. The densities and moisture contents were measured using a nuclear densometer. Samples were taken from each location and oven dried to check the accuracy of the nuclear densometer. The unsurfaced road was being used as part of an active timber sale at the time of testing.

The unsurfaced road was a contractor-constructed spur road, not a "Specified" Forest Service designed road. It was constructed along the top of a ridge using minimal cuts and fills. The road had approximately 500 feet of sustained 32% grade. This grade was measured using a clinometer. Density and moisture content measurements were taken on two occasions, once during the first week of log haul and once at the end of log haul. The road was used for about four weeks from the end of August to the end of September. Roughly 1.5 million board feet of logs were hauled. The road was not compacted prior to log haul.

The soil this road was built on was a fine grained, silty sand. From existing information, the liquid limit was 33% moisture content and the soil was non-plastic. The California Bearing Ratio was reported to be 8.

The contractor reported that only half a day of hauling was lost to bad weather. The shut down in hauling occurred on the third day of a storm which delivered 0.9 inches of rain in one day. The three-day total of rain was 1.73 inches. It should be noted that this is one of the sandier soils in the Siuslaw National Forest Soil Survey. The first set of density and moisture content readings were taken one day after the hauling was shut down due to rain. It rained while we were taking measurements. I observed that the hard-packed, smooth surface the truck tires were riding on became slick when it was wetted by a rain shower. However, the surface remained slick for only about 15 minutes. Empty log trucks had no noticeable trouble backing down unassisted and loaded log trucks climbed out with the usual amount of assistance during the 15 minute period.

The soil was rapidly drained and it did not appear to lose a significant proportion of its strength even when it was wet.

The point of this example is that during the summer season it took more than an isolated single shower or even one day of rain to shut down hauling on the 32% road with a firm running surface.

The results of the moisture and density testing are summarized in the graphs and tables that follow (See Figures 15-17).

It was observed during the moisture content testing that fill areas collect water. Fills that are just downhill from through cuts appeared to have the greatest increase in moisture content. On the soil road there were two fill areas, a one-foot fill and a four-foot fill. The moisture contents in the wheel tracks in the one-foot fill ranged from 28% to 30.6% moisture following three days of rain. In a through cut on the same day, the moisture content ranged from 21.7% to 21.8%.

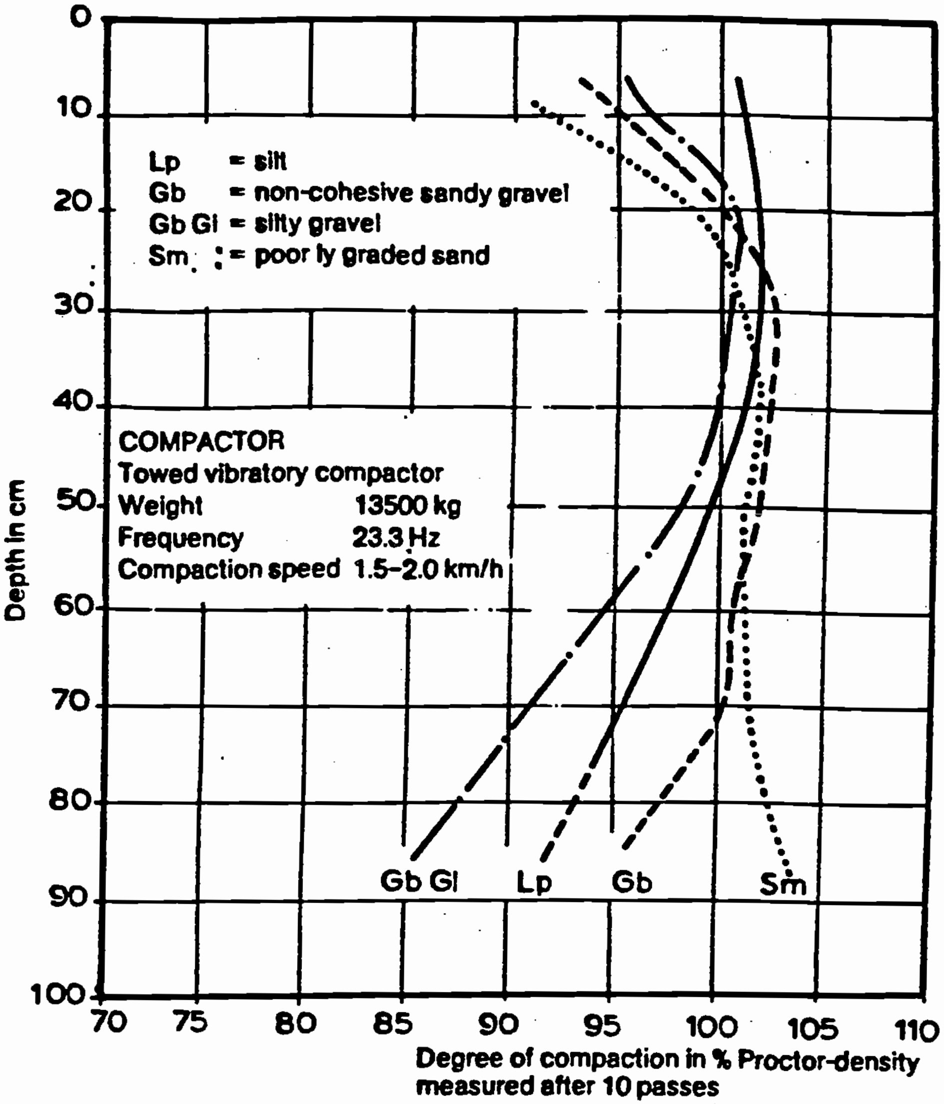

Figure 15. Density achieved after 10 passes with a heavy towed vibratory compactor. (Fischer, 1975)

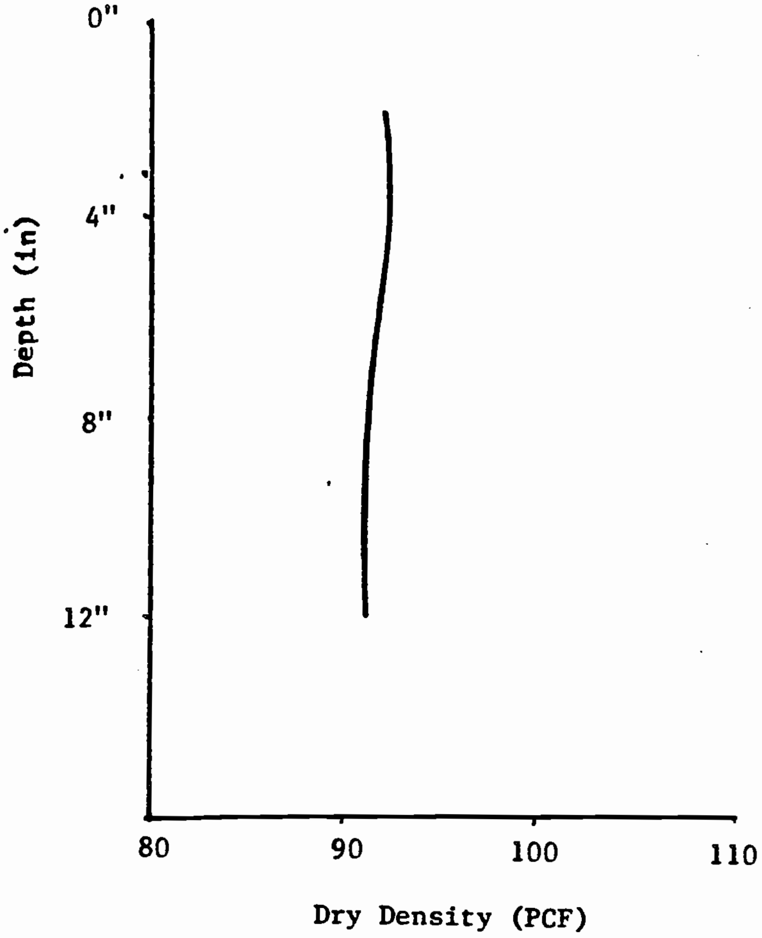

Figure 16. Average density in wheel tracks on 32% grade in silty sand.

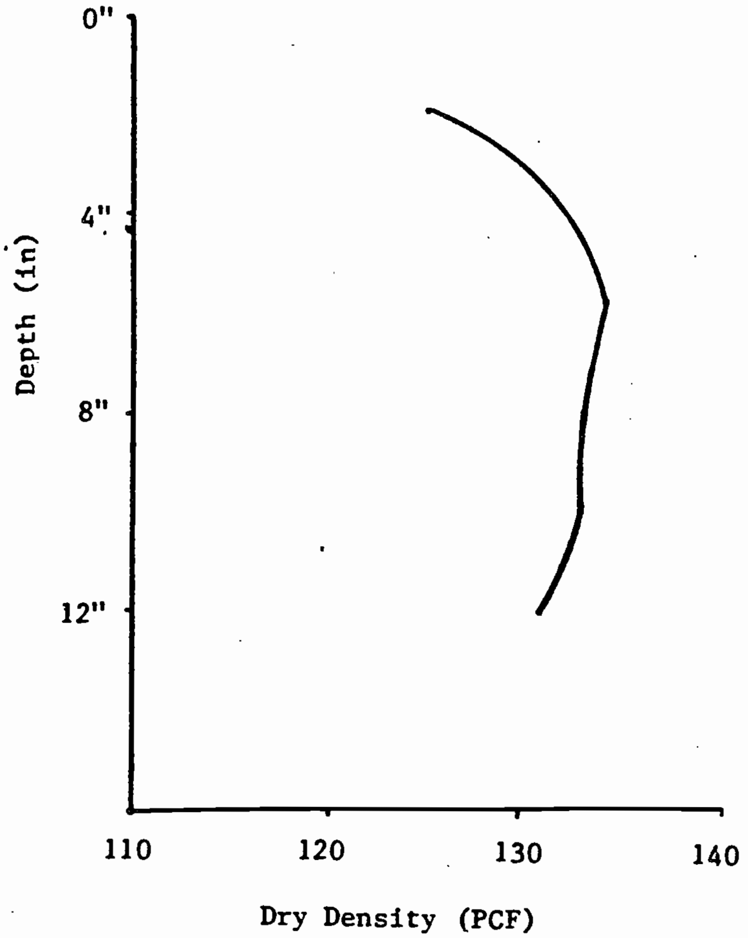

Figure 17. Average density in wheel tracks on 20% grade in crushed rock aggregate.

After two weeks of relatively dry weather, additional measurements were taken. The moisture readings in the four-foot fill ranged from 21.6% to 23.2% at a 2" depth. The through cut showed moisture contents of 23.8% to 24.5% at a 2" depth. On this occasion, the moisture contents in a four-fill were measured and they ranged from 28.6% to 29.1%. During this short rainy period, the fills in this unsurfaced road soaked up moisture faster than through cuts and the deeper fills tended to hold moisture longer than shallow fills.

It is interesting to note that a fill depth of one foot absorbed 10% more moisture content after just a few days of rain.

Measurements of moisture content and density were taken on crushed rock aggregate roads on the same dates that measurements were taken on the unsurfaced roads. The crushed rock surfaced road was designed by the Forest Service and built according to its specifications. This road is located on the same major ridge system where the moisture and density tests were done on the unsurfaced road. The results of the moisture and density tests are presented below.

This road had 8" of rock. The road extended downhill from a main road to a landing for about 500 feet at about 20% grade. The road surface was compacted at the time of construction. The readings were taken after the sale had been logged and the road had been hauled upon.

The crushed rock on this road came from the Swisshome Quarry. It was crushed to a 1" minus gradation and when it was sampled from the stockpile it had a maximum density of 143.7 PCF and an optimum moisture content of 8.6% (Harvard 106 OSHD). When originally tested, 6% passed the #200 sieve. After haul, the sample taken had 11% passing the #200 sieve and showed about a 10% reduction in the weight of sample retained in the #40, #30, #10 sieves. The important difference between the crushed rock aggregate and the soil is that the crushed rock surface had a much lower moisture content than the soil road, highlighting the ability of the crushed rock aggregate to be used in wet weather. The moisture content in the top 2" of the crushed rock road averaged 5.83% after 1.73" of rain, in a 3-day storm.

The density tests showed a drop off in density in the surface of the crushed rock aggregate. The fine-grained soil showed no drop off in density.

Figure 15 shows the results of compaction tests done by Clark Schied (1975) on a fine sandy silt and cohesive sandy gravel. Their tests provide a similar pattern of results. The silt can be compacted to its maximum density close to the surface while the gravel and crushed rock aggregate show a drop in density near the surface. The reasons for this phenomena are beyond the scope of this paper, but it raises construction. The readings were taken after the sale had been logged and the road had been hauled upon.

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Conclusion

The results of the density and moisture content testing show that the soil surface is much more susceptible to moisture than crushed rock aggregate and the moisture content changes more rapidly for the soil than for the crushed rock aggregate. The soil achieved greater than 95% of T-99 density in the wheel tracks as a result of truck traffic. The soil, when compacted, was able to support log haul traffic even when it had moisture contents of 30%.

APPENDIX II

Laboratory Testing

LABORATORY TESTING

Introduction

There is no consensus on surfacing requirements for steep roads in the Oregon Coast Range. In order to evaluate the usefulness of a road surface, the bearing capacity and the traction that can be developed from any surface must be known. Direct shear tests or tri-axial shear tests are performed to estimate the shear strength for soil as a road surface. Alto (1982) reported results from tests on soils from the Oregon Coast Range using consolidated-undrained triaxial tests with backpressure saturation. Direct shear ests performed for this project were compared against those results. The triaxial testing procedure is more applicable to landslide stability and structures than the direct shear tests (Burmister 1954). Direct shear data provides a closer approximation to the shear process between a tire and road surface.

Traction is limited to the lessor of soil-to-soil shear strength or soil-to-rubber shear strength. An objective of this laboratory testing was to identify whether the soil-to-soil coefficient of friction or the soil-to-rubber coefficient of friction is more limiting.

Stryker (1977) has identified traction as the limiting factor in log truck gradeability on adverse grades. The coefficient of traction or friction is represented in the literature as a ratio of shear force or strength divided by normal force. Traction coefficients are available for a number of soil and tire combinations. Descriptions of road conditions are not precise and require some interpretation of ground conditions. For example, the "Caterpillar Performance Handbook" reports the coefficient of traction for "rubber tires" on "firm earth" to be 0.55. Stryker, in a composite table from Taborek (1957) and Western Highway Institute (1976), reports that the road-tire adhesion coefficient for "dry earth" as 0.65. If both accurately describe the soil, a more precise definition is required to avoid confusion.

A possible explanation for the variation in reported coefficient of traction between sources is that soil is highly variable and that the maximum coefficient of friction that can be developed on a soil is affected by both density and moisture content. Laboratory tests were conducted under different moisture contents to determine the relationships between coefficient of traction, moisture content and density.

Methods

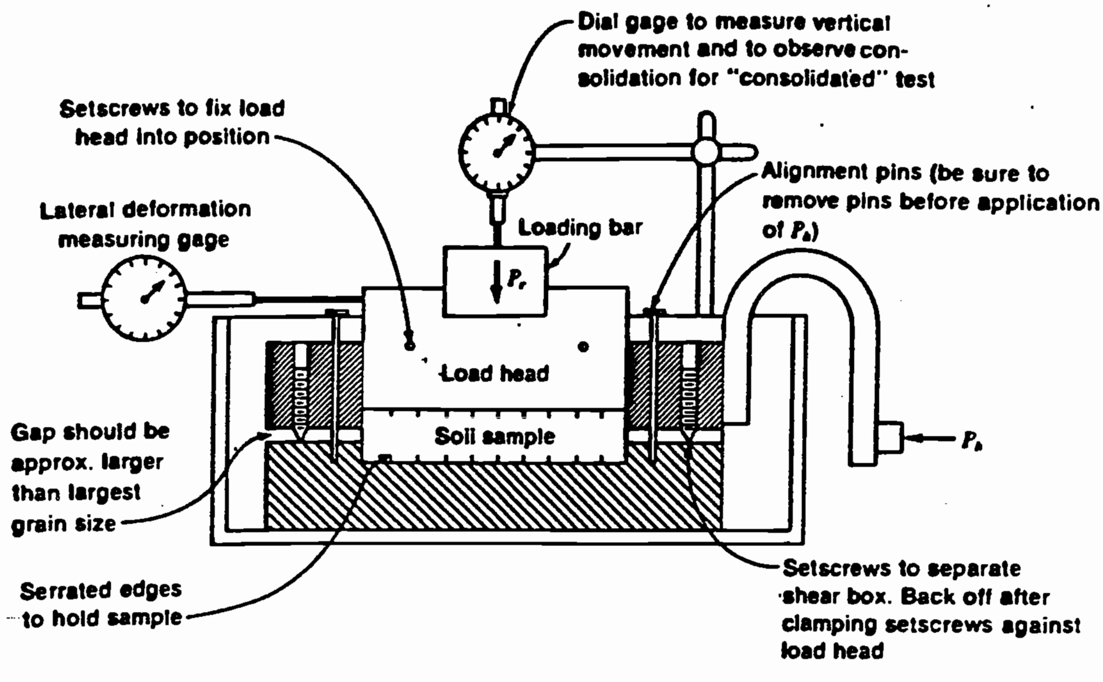
Soil samples were obtained from the roadway of unsurfaced roads. Density and moisture content tests of the unsurfaced roads showed that during log haul in the summer the soils were compacted to greater than 95% of T-99 density in the wheel tracks. Soil samples were removed to the laboratory and compressed to densities similar to those found in the wheel tracks.

For comparative purposes, the direct shear tests were performed in a saturated and unsaturated condition using the apparatus shown in Figure 18. Tests were conducted at the highest rate of strain (.533 in/min.) obtainable with the equipment because tire slip produces a high rate of strain. These tests will be compared with tests where the effect of capillary adhesion is compensated for by using back pressure saturation.

Results

Results are displayed in the Figures 19-21. The first three figures show cohesion and internal angle of friction for the three soils tested. The solid line is the direct shear results using a high rate of strain and the dotted line is the results of test done by Alto (1981). Alto tested similar soils from the same area using a triaxial test. The results from the direct shear tests are similar to Alto at higher normal pressures. The direct shear results differ from Alto at low normal pressures. A possible explanation for the difference is the high strain rate and the effect of moisture in the direct shear tests.

It is interesting to note that the effect of capillary adhesion disappears at normal pressures in the range where logging truck tires normally operate (80-90 psi) normal force.



Line details of shear box/test

Figure 18. Illustration of direct shear apparatus.

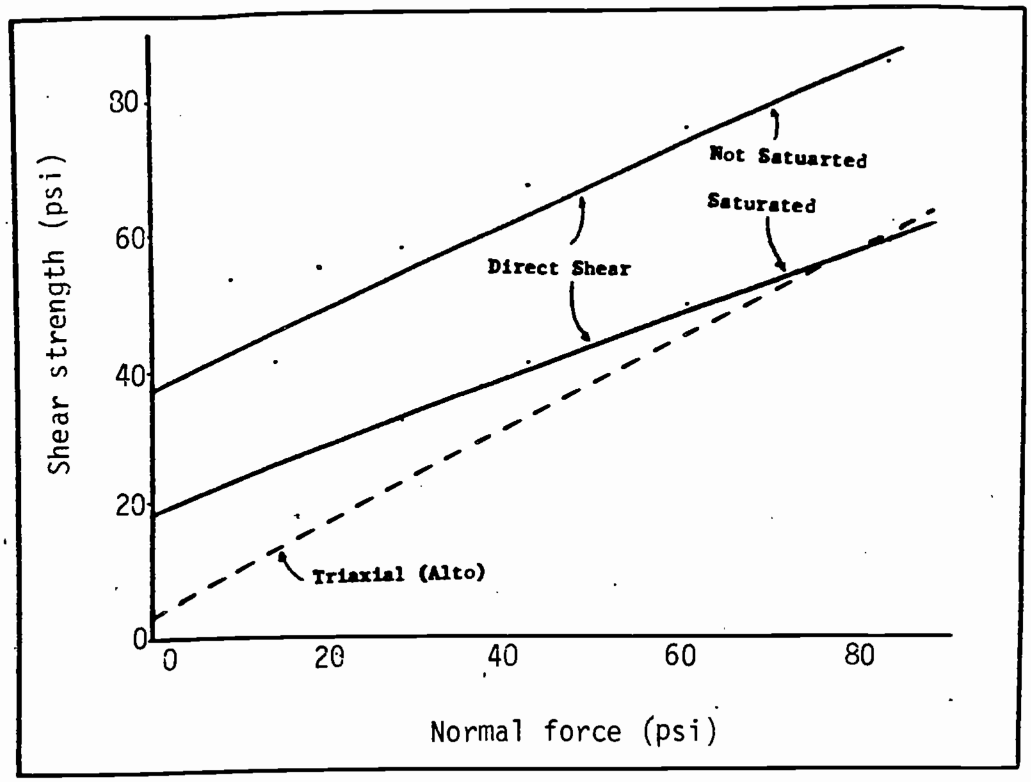


Figure 19. Direct shear and triaxial tests of silt compared.

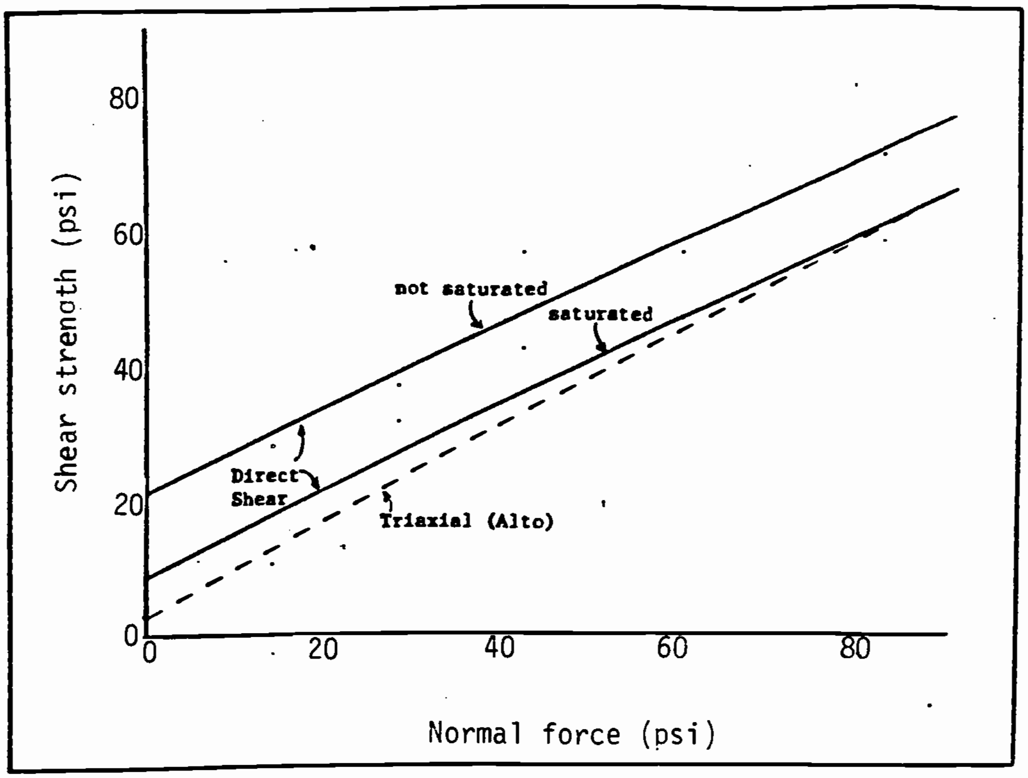


Figure 20. Direct shear and triaxial tests of silty sand compared.

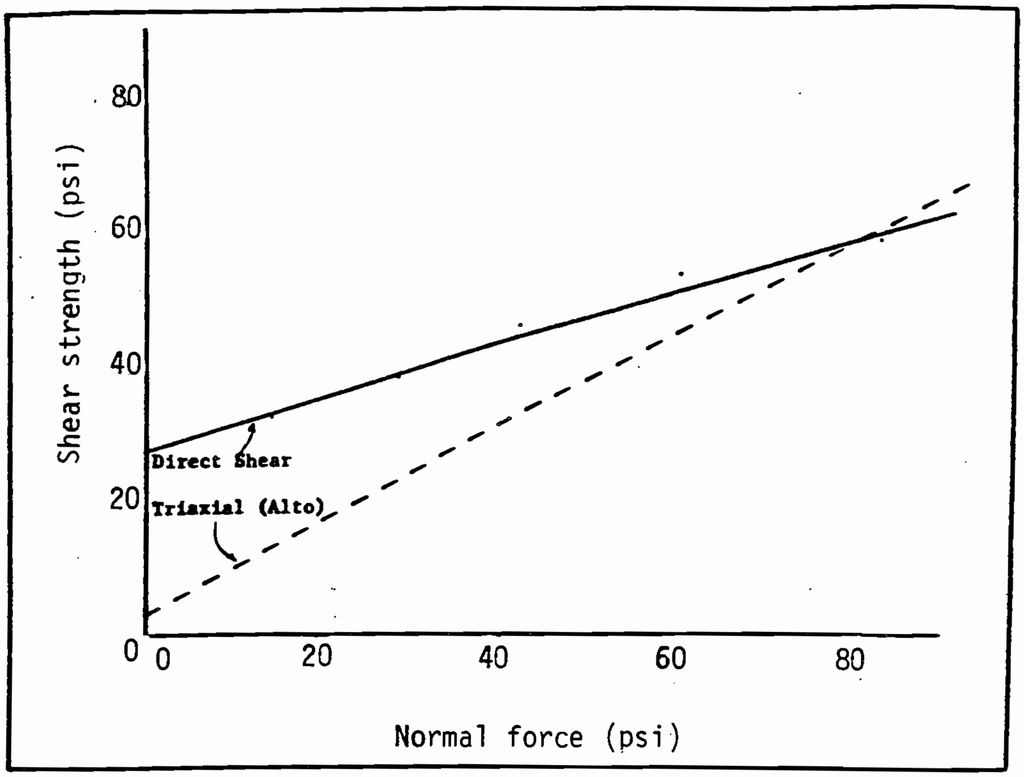


Figure 21. Direct shear and triaxial tests of soil from the Thompson drainage road compared.

Two of the soils were tested at a saturation ratio as close to 100% as could be achieved using the direct shear apparatus to show the effects of saturation on strength. For these soils, tests showed soil strength is reduced, even in soils compacted to 95% of T-99 density.

Figures 22 through 24 show the maximum soil-to-soil coefficient of friction for the test soils in various conditions.

The soil-to-soil coefficient of friction varies as a function of normal force. The soil-to-soil coefficients of traction observed at 83 psi normal force ranged from 1.00 to 0.70 for unsaturated soils. For saturated soils, the soil-to-soil coefficients of traction were both 0.70 at 83 psi normal force. For a sandy silt with 35% passing the #200 sieve, a reduction in the soil-to-soil coefficient of traction from .85 to .70 at 83 psi normal force was observed when the soil was saturated.

For a silt with 95% passing the #200 sieve, the soil-to-soil coefficient of traction dropped from 1.00 to 0.70 at 83 psi normal force. If density is lost or never obtained (for example, construction during wet weather), these fine-grained soils could be expected to have very little shear strength.

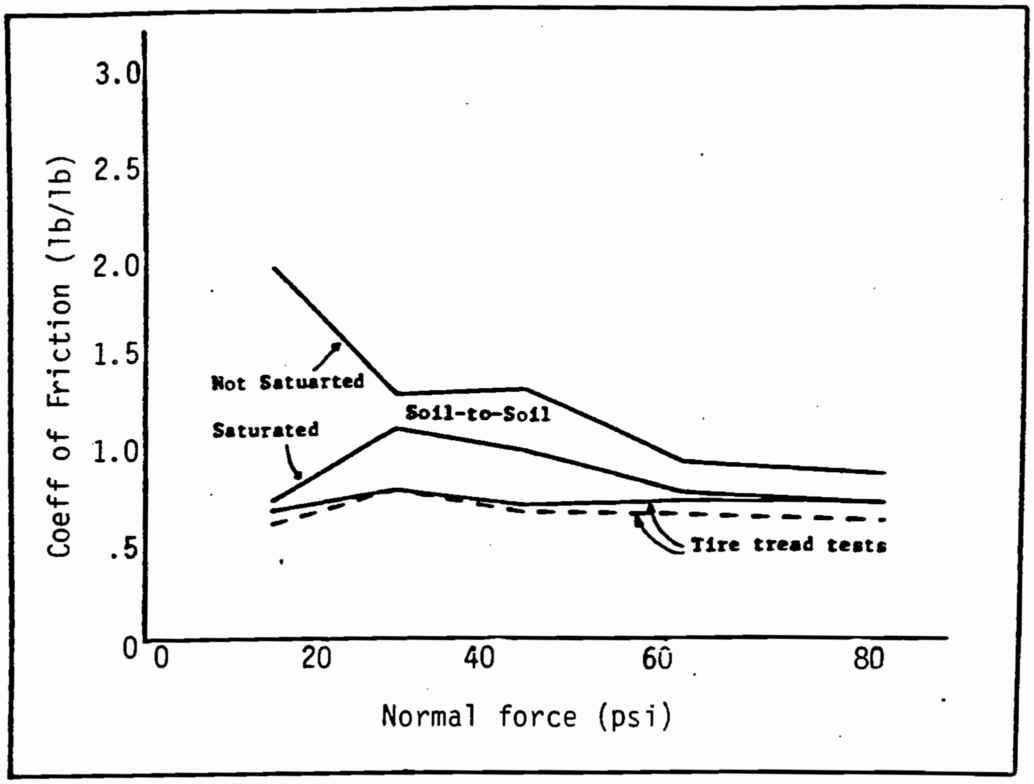


Figure 23. Soil-to-soil coefficient of friction compared to Tire tread-to-soil coefficient of friction for silty sand.

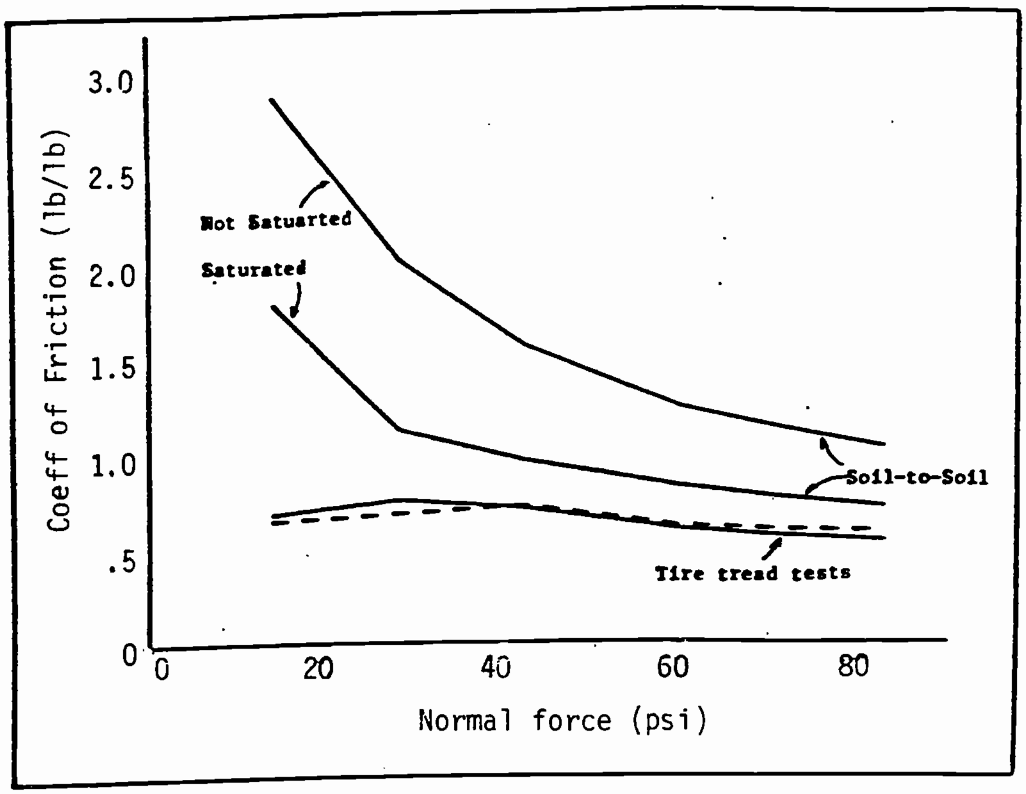


Figure 24. Soil-to-soil coefficient of friction compared to Tire tread-to-soil coefficient of friction for silt.

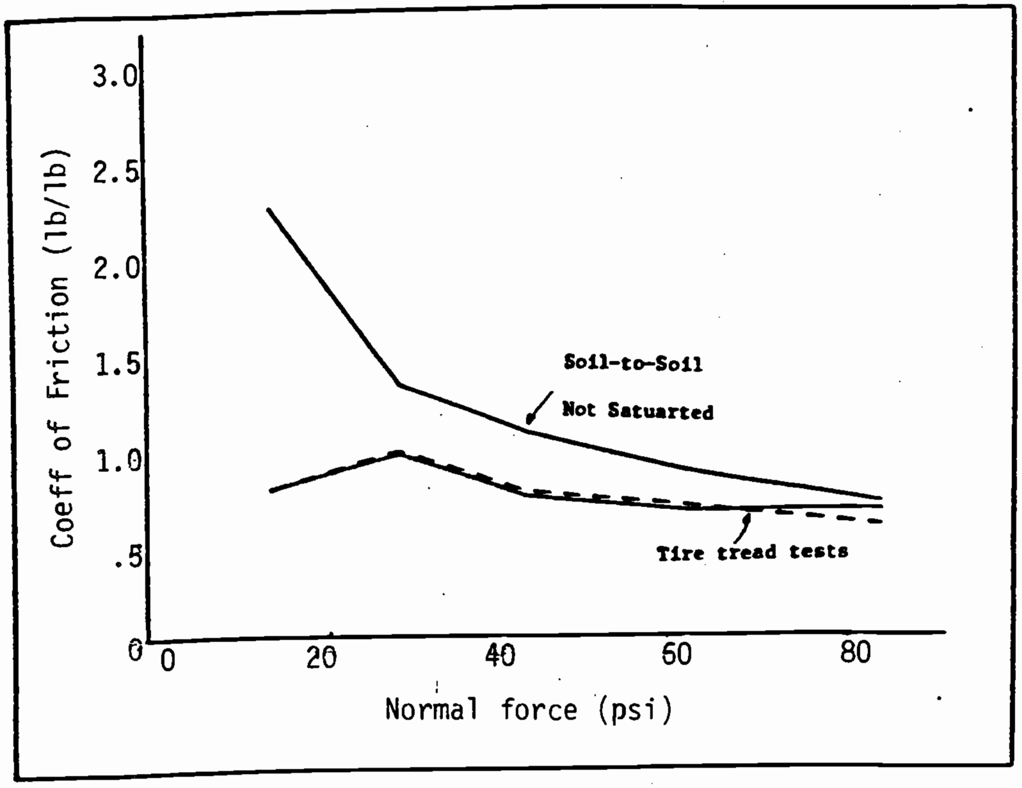


Figure 25. Soil-to-soil coefficient of friction compared to Tire tread-to-soil coefficient of friction for soil from the Thompson drainage road.

If a log truck is traction limited, the gradeability is dependent upon the percentage of the soil-to-soil shear strength that can be developed between the rubber tires tires and the soil. How efficient are rubber tires and conventional log trucks at mobilizing shear strength of the soil? No information was identified in the literature search. To obtain a preliminary idea of the ability of tires to use soil-to-soil shear strength, a field test was made on the Mapleton District of the Siuslaw National Forest.

The field location selected was an unsurfaced road where loaded log trucks had climbed an adverse 26.4% grade unassisted. The soil on this road was sandy silt with 75% passing the #200 sieve. The road was watered and rolled nightly and the trucks would occasionally spin out and need assistance. The road was fairly straight and there was no opportunity to coast up the hill using momentum. This situation was one in which loaded log trucks were as close to a purely traction limited gradeability as I could find. Sessions' log truck gradeability model (Appendix IV) was used to calculate the coefficient of traction necessary for a loaded log truck to climb a 26.4% grade without an assist. It was assumed that rolling resistance was 60 lb/ton (Caterpillar Performance Handbook) and the geometry of the log truck was the same as Stryker (1977) found in his study of log trucks in this area. The calculated coefficient of traction was 0.61. With this information, we can calculate what proportion of the potential soil-to-soil shear strength was realized between the tire and the soil.

$$\frac{\text{Coefficient of traction developed by tires}}{\text{Coefficient of traction available from soil}}$$

$$.61/.70 = 87\% \text{ efficient}$$

For this example it appears that rubber tires on firm earth at 80 to 90 psi normal force were about 87% efficient. In order to make definitive statements about tire efficiency, many more field studies would be needed.

To be operational, a predictive technique would need to be developed for the coefficient of traction. As direct shear tests were being conducted on soil-to-soil properties, it was desirable to extend the process to test soil-to-rubber in direct shear.

Tire Tread Tests

Truck traction tire recap tread was obtained from a local tire dealer (Les Schwabe) and was cut to fit in the upper half of the direct shear apparatus. The tire tread was placed in the upper half of the direct shear machine and the compacted soil sample was constructed so that it protruded from the bottom half of the direct shear apparatus.

The apparatus was then loaded to provide various normal forces and the tread was forced to slide across the top of the soil. The results from this testing are presented in the Figure 25. Two samples of tire tread were used. There was no apparent difference in the coefficients of traction produced by the samples. Results of the tire tread tests can be compared against the calculated coefficient of traction on the 26% road as well as the soil-to-soil coefficient of traction. Figures 22-24 show these comparisons.

In the case of the Thompson (26% road) drainage road, the tire tread tests agreed reasonably well. However, there is a great deal of work that needs to be done to verify this type of test. It is not a standard soil test procedure and may not be an accurate model of the way a tire interacts with the road.

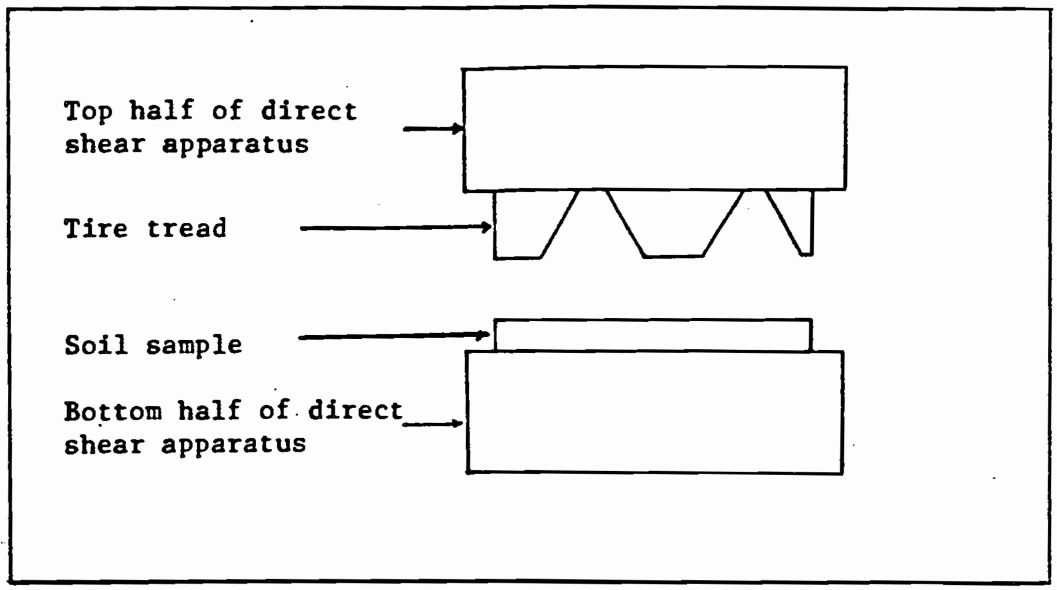


Figure 22. Direct shear apparatus adapted to accept a portion of a tire tread.

APPENDIX III

Economic Analysis

ECONOMIC ANALYSIS

Cost model

To compare road alternatives, an economic model was made. The form of the model is to sum all the costs for all the segments of road. For example, excavation cost varies as a function of side slope, road width, material type, and, indirectly, as a function of road grade through road location.

The general form of the model is:

Total cost = $\Sigma\Sigma\Sigma\Sigma\ (V_{ijkl})\ (X_{ijkl})\ (C_{ijkl})$

where

V = the variable ie: Excavation volume.

X = the segment length of that variable for a specific i,j,k,l set of conditions.

Cost = the cost per unit for that specific i,j,k,l set of conditions.

A list of the variables and an explanation of how they are affected by road grade as follows:

Total Cost = $\Sigma\Sigma\Sigma\ (\text{Design Cost})_{ijk}\ (X_{ijkl})\ (\text{Cost}_{ijk})$

$+\ \Sigma\Sigma\Sigma\ (\text{Excavation Volume})_{ijkl}\ (X_{ijkl})\ (\text{Cost}_{ijkl})$

$+\ \Sigma\Sigma\Sigma\ (\text{End Haul})_{ij}\ (X_{ij})\ (\text{Cost}_{ij})$

$+\ \Sigma\Sigma\Sigma\ (\text{Drainage})_{ijkl}\ (X_{ijkl})\ (\text{Cost}_{ijkl})$

$+\ \Sigma\Sigma\Sigma\ (\text{Rocking Cost})_{ijk}\ (X_{ijkl})\ (\text{Cost}_{ijk})$

$$+ \Sigma\Sigma\Sigma\ (\text{Haul})_{ijk}\ (X_{ijk})\ (\text{Cost}_{ijk})$$

$$+ \Sigma\Sigma\Sigma\ (\text{Maintenance})_{ijk}\ (X_{ijkl})\ (\text{Cost}_{ijk})$$

\+ other costs not affected by road grade

Condition descriptions for variables in the model.

Excavation
i = side slope
j = road width
k = grade
l = material type

Drainage
i = max intensity rainfall
j = erosion hazard
k = grade

Haul
i = road width
j = grade
k = surfacing

Road Maintenance
i = surfacing
j = grade
k = use level

Rocking Cost
i = Rock Quality
j = grade
k = surface treatments to improve

End Haul
i = distance of haul
j = excavation volume

Table 4. Elements that vary as a function of road grade:

As road grade increases--

	Price per unit	Quantity
Excavation	Roughly stays the same	Decreases rapidly when road is kept on the ridgetop
End Haul	Could increase or decrease	Would vary with excavation volume
Rocking costs	Increase slightly	Decrease if road road length decreases sufficiently
Culverts	Same	Increase
Blading Maintenance	Increase on roads steeper than 16%	Decreases: Less length to maintain
Ditch Maintenance	Increases	Decreases: Less roads on sidehill and less keep open roads
Surface Treatments to improve traction	Same	Increases
Log Haul Unassisted	Increases slightly	Same
Log Haul Assisted	Same	Increases
Design and Administration	Increases cost 20% to 40%	Same
Clearing and Grubbing	Decreases for Ridgetop roads	Decreases for Ridgetop roads

Variables that are a function of road grade

Factors Affecting Excavation Volume

As road grade increases:

- Road length can be developed in most cases by increasing road grade.
- Running width can increase for roads requiring an assist. A wider road surface may be required to accommodate an assist vehicle and truck drivers would like a wider surface to maneuver on steep grades (Rickard, 1984).
- Side slopes can decrease if the roads are kept on ridgetops. Generally, the reason that steep roads are being built is to avoid sidehill construction.

Factors Affecting Rocking Cost

As road grade increases:

- Road length decreases see excavation
- Road width increases see excavation
- Depth of rock is unchanged: usually depth of rock would not change as a function of grade.
- Cost per cubic yard of rock increases: slightly as tighter control on rock gradation is required. The cost of additives would increase the cost of rock.

The need to improve traction could cause the use of these additives.

- Compaction cost for crushed rock surfaces increases as road grade increases. At grades steeper than 20% compaction may require an assist.

Factors Affecting Drainage Cost

As road grade increases:

- Road length decreases (see Excavation)
- Erosion hazard remains unchanged but the effect of increasing road grade increases water's erosive power in a non-linear way. For example, increasing gradient four times would increase the sediment carrying capability of water by 5 times (Forbes, 1955).
- Erosion control costs increase. Measures such as rocking ditches mulching or rocking a road that has been put to bed to keep erosion down.

Factors Affecting Maintenance

As road grade increases:

- Length of road tends to decrease
- Level of use tends to decrease
- Damage from vehicles spinning wheels or becoming immobilized increases

- Ditch maintenance tends to increase because of the increased erosive power of water.

  The cost of removing cut slope slumps increases because of the increased difficulty of equipment operating on steep road grades.

Factors Affecting Log Haul Cost

As road grade increases:

- Round trip time increase (Byrne, et al. 1960)
- The need for assists increases

BREAKEVEN EXAMPLE

An example to find the breakeven volume between two road alternatives follows. Alternative 1 is a 1.5-mile road of 16% grade that would permit haul by unassisted trucks. The 16% road is constructed on the sidehill and has a cost of $375,000. Round trip haul time on the 16% road is 20 minutes. Alternative 2 is a 1-mile road of 24% grade that would require the log trucks to be assisted. The 24% road is a ridgetop road and has construction cost of $100,000 and a round trip haul time of 28 minutes. Both roads would be closed with water-bars and out-sloped.

The costs are as follows:

	Sidehill alterantive 16% grade	Ridgetop alternative 24% grade
Road length	1.5 mi	1 mi
Excavation +end haul+ placement of waste	58,000 yd/mi @ 3 $/yd $261,000	11,300 yd/mi $34,000
Rocking cost	2,500 yd/mi @ 15 $/yd $56,000	2,500 yd/mi @ 20 $/yd $50,000
Drainage	150' culvert spacing 53 culverts @ $300 $15,000	
Clear and Grub Misc.	$28,000	$ 5,000
Construction Total	$360,000	$ 89,000
Close Road	$ 5,000	$ 5,000

Haul Cost

Local truck costs are $60 per operating hour. Assist vehicle cost is $40 per standby and operating hour. The cost of the assist vehicle in terms of $/mbf can be estimated as

$/mbf = ($40/hr x 8 hr/da)/60 mbf/day = $5.33/mbf

	16% road	24% road
Truck cost per mbf	$\frac{20 \text{ min} \times \$1/\text{min}}{5 \text{ mbf/trip}}$ $4.00/mbf	$\frac{28 \text{ min} \times \$1/\text{min}}{5 \text{ mbf/trip}}$ $5.60/mbf
Assist cost per mbf	---	$5.33
Total round trip Haul cost	$4.00/mbf	$10.93/mbf

Assume one move-in and move-out per 5.0 mmbf and the difference in gradient requires one extra tractor per move. If the cost of an extra tractor assist is $1000 per move in, then the 24% road alternative would have an <u>extra</u> cost of $2000 per each 5.0 mmbf.

To find the breakeven volume, the difference in fixed road construction costs should be compared against the difference in variable haul costs per mbf. From our example this would be:

16% road		24% road
365,000 + 4 (V)	=	94,000 + 10.93 (V) + 0.40 (V)
271,000	=	7.33 (V)
Breakeven Volume	=	36,971 mbf

For this example, if the expected volume to be hauled is greater than 37 mmbf then the 16% road should be built. If the road would be used for a number of entries, then the discounted costs of reconstruction and future haul would need to be included. The effect of future entries would, in general, reduce the breakeven volume required.

APPENDIX IV

Gradeability Models

This explaination of the gradeability model is taken from Sessions classnotes

Model

The basic model for developing gradeability equations is the common tractor trailer combination or semi-trailer combination. When modeling the loaded log truck pole trailer combination, the front bunk is assumed to function as the fifth wheel of the semi-trailer in transferring horizontal and vertical loads from the trailer to the truck tractor. This appears to be a reasonable assumption at all except very steep gradients when the coefficient of friction between the bunks and the logs is not sufficient to permit transmission of lateral loads between load and the tractor and the reach must be secured to prevent loss of the trailer. Modeling of the unloaded "piggyback" truck and trailer is identical to analyzing a simple truck.

The Unloaded Logging Truck

Modeling of the unloaded "piggyback" truck and trailer is identical to analyzing the simple truck. There are three common formulas in use. The Western Highway Institute formula (1976) estimates piggyback log truck gradeability as

$$P = 100 [(x_1/x_3) (\mu+f) - f] / [1 - (\mu+f) (y_1/x_3)]$$

When height to the center of gravity is assumed zero, the equation reduces to

$$P = 100 (x_1/x_3) (\mu + f) - f$$

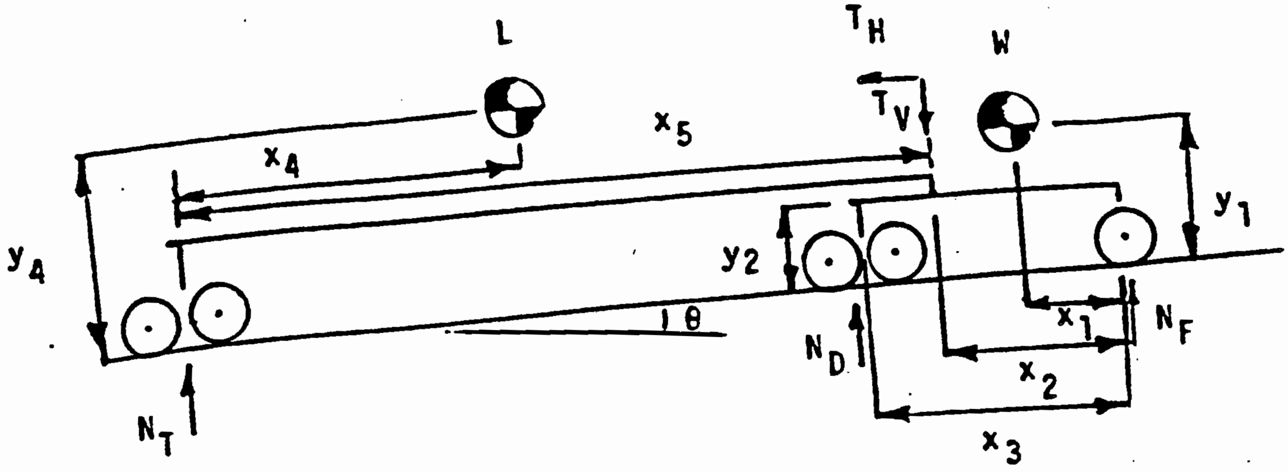
Stryker (1977) derives an expression for the piggyback log truck which estimates gradeability as:

$$P = 100 (\mu x_1) / (x_3 - \mu y_1)$$

Stryker's formula, modified to include rolling resistance, is

$$P = 100 \mu (x_1 - f x_3) / (x_3 - \mu y_1)$$

Figure 26. Truck geometry and load distribution nomenclature and data for sample calculations (Sessions,1984).



Symbol	Description	Example Data Conventional	CAB Over Engine
W	Weight of truck tractor or piggyback combination	14000 lb	14000 lb
L	Weight of trailer and load	62000 lb	62000 lb
X_1	Distance from front axle to c.g. of truck tractor	7.0 ft	5.0 ft
X_2	Distance from front axle to king pin or front bunk	19.0 ft	13.0 ft
X_3	Wheelbase of truck tractor	20.0 ft	14.0 ft
X_4	Distance between center of trailer tandem and c.g. of load plus tractor	14.25 ft	14.25 ft
X_5	Distance between center of trailer tandem and king pin or front bunk	30.0 ft	30.0 ft
Y_1	Height to c.g. of truck tractor	3.5 ft	3.5 ft
Y_2	Height to top of king pin or top of front bunk	4.9 ft	4.0 ft
Y_4	Height to c.g. of loaded trailer	7.0 ft	7.0 ft
μ	Coefficient of traction	0.55	0.55
f	Coefficient of rolling resistance	0.03	0.03

Loaded Log Truck

Five formulas are available to compute gradeability of loaded tractor-trailer combinations. Equation 1 as presented by McNalley (1976) is

$$P = \frac{100\ \mu\ ND^*/(L+W)}{1 - (\mu\ y_2/x_3)} - 100\ f\ [(1-ND^*/(L+W)] \qquad \text{Eq. 1}$$

where

P = traction limited gradeability, %

ND* = level road static axle weight on drive axles

Equation 2 can be derived from Equation 1 by omitting rolling resistance f, and the front bunk height, y_2 (assuming that both are zero.) These assumptions result in

$$P = 100\ \mu\ ND^*\ /\ (L+W) \qquad \text{Eq. 2}$$

Note that in both equation 1 and 2 the height to the center of gravity of the trailer and tractor are not considered. The location of the bunk is also not required. The only vehicle information required is wheel base and axle loading measurements on level ground. Using truck mounted scales and a measuring tape the vehicle information for Equation 1 and 2 is readily available.

A third formula presented by the Western Highway Institute (1976) which requires similar information to Equation 1 is

$$P = 100\ (\mu+f)\left[\frac{ND^*}{L+W} + \frac{\mu\ ND^*/(L+W) - f\ NF^*/(L+W)}{x_3/y_2 - \mu - f}\right] - 100\ f \qquad \text{Eq. 3}$$

A fourth formula by Stryker (1977) includes the height to the center of gravity of the trailer and tractor, but assumes the normal forces on the drive and trailer axles are equal and does not consider rolling resistance. The traction limited grade using this formula is

$$P = \frac{100\ [W\ x_1 + L\ (x_2 + x_5 - x_4)]/(L+W)}{x_2+x_3+x_5 - \mu\ (y_1\ W + y_4\ L)/(L+W)} \qquad \text{Eq. 4}$$

A fifth formula considering rolling resistance, vehicle geometry and the effects of dynamic weight transfer is derived in the Appendix. This formula is

$$P = 100 \tan\theta \qquad \text{Eq. 5}$$

$$\text{Tan}\ \theta = \frac{A\ (\mu/x_3) - f\ (L+W)\ (y_2\ f + x_5)}{-B\ (\mu/x_3) + (L+W)\ (y_2\ f + x_5)}$$

where,

$$A = [L\ \{y_2\ f\ (x_2+x_5-x_4)+(x_2\ x_4)\}+(W \cancel{+} x_1)\ (y_2 \cancel{+} f+x_5)]$$

$$B = [L\ \{y_2\ (x_2+y_4 \cancel{+} f+x_5)-(x_2\ y_4)\} + (W \cancel{+} y_1)(y_2 \cancel{+} f+x_5)]$$

Derivation of equation 5 is as follows:

Considering first the free body diagram of the truck tractor:

Summing forces in the x-direction,

$$T = T_H + f\ N_D + f\ N_F + W \sin\theta \qquad (A1)$$

Summing forces in the y-direction,

$$N_D + N_F = T_V + W \cos\theta \qquad (A2)$$

Summing moments about the contact point of the front tires,

$$N_D\ x_3 = T_V\ x_2 + T_H\ y_2 + W\ y_1 \sin\theta + W\ x_1 \cos\theta \qquad (A3)$$

Considering the free body diagram of the trailer:

Summing forces in the x-direction,

$$T_H = L \sin\theta + f\ N_T \qquad (A4)$$

Summing forces in the y-direction,

$$T_V = L \cos\theta - N_T \qquad (A5)$$

Summing moments about the "contact" point of the rear trailer tandems,

$$L\ x_4 \cos\theta + T_H\ y_2 - T_V\ x_5 - L\ y_4 \sin\theta = 0 \qquad (A6)$$

These force and moment balances must be combined with the requirement that at maximum gradeability the effective thrust of the driving axles is limited to

$$T = \mu N_D \tag{A7}$$

We have 7 equations in seven unknowns: θ, N_T, N_D, N_F, T_H, T_V, and T. Solving these equations simultaneously yields

$$\theta = \frac{A\ (\mu/x_3) - f\ (L+W)\ (y_2\ f + x_5)}{-B\ (\mu/x_3) + (L+W)\ (y_2\ f + x_5)} \tag{A8}$$

where,

$$A = [L\ \{y_2\ f\ (x_2+x_5-x_4)+(x_2\ x_4)\}+(W\ x_1)\ (y_2\ f+x_5)]$$

$$B = [L\ \{y_2\ (x_2+y_4\ f+x_5)-(x_2\ y_4)\} + (W\ y_1)(y_2\ f+x_5)]$$

$$T_H = \frac{L\cos\theta + (L\sin\theta)/f) - (L\ x_4\cos\theta - L\ y_4\sin\theta)/x_5}{(y_2/x_5 + 1/f)} \tag{A9}$$

$$T_V = L\cos\theta - N_T \tag{A10}$$

$$N_T = (\ T_H - L\sin\theta\ )\ /\ f \tag{A11}$$

$$N_D = (\ T_V\ x_2 + T_H\ y_2 + W\ y_1\sin\theta + W\ x_1\cos\theta\ )\ /\ x_3 \tag{A12}$$

$$N_F = T_V + W\cos\theta - N_D \tag{A13}$$

$$T = T_H + f\ N_D + f\ N_F + W\sin\theta \tag{A14}$$

Assists

The additions made to Sessions Gradeability model necessary to estimate the effects of an assist vehicle pushing or pulling the loaded truck up an adverse grade are.

$$PA = (UTR * WTR * COS(THEA)) - (WTR * SIN(THEA))$$

Where

UTR = coefficient of traction for the assist vehicle

WTR = weight of assist vehicle

THEA= road grade in degrees

This thrust is added to the thrust provided by the drivers on the log truck. The total thrust is subtracted from the sum of the resisting forces.

$$T = TH + F*ND + F*NF + W*SIN(THEA) - (U*ND + PA)$$

Where

T = Thrust required to move vehicle combination

TH = Horizontal force transmitted from the bunk logs to the bunk

F = Rolling resistance

ND = Normal force on drivers

NF = Normal force on front wheels

W = Weight of the tractor portion of the truck

Thea = Road grade in degrees

U = Coefficient of traction for the drivers on the log truck

PA = Thrust available from the assist vehicle

ALL-WHEEL DRIVE

The equation for thrust required for all-wheel drive is much the same as the equation developed for assist vehicles.

$$T = TH + F*ND + F*NF + W*SIN(THEA) - (U*ND + U*NF)$$

Where

U*NF = The thrust available from the front wheels

LOADED LOG TRUCK GRADEABILITY (DOWN)

Thrust necessary to resist is :

$$T = Th - fNd - fNf + W \sin (TH)$$

where

f = rolling resistance

$Nf = Tv + W \cos (TH) - Nd$

$Nd = (Tv\ x2 - Th\ y2 - W \sin (TH)\ y1 + W \cos (TH)\ x1)/x3$

$Tv = L \cos (TH) - Nt$

$Nt = (L \sin (TH) - Th)/f$

$Th = (L \cos(TH)\ x4 - Tv\ x5 + L \sin (TH)\ y4)/y2$

Subject to the braking constraints

$T = Tf + Td + Tt$

$Tf <= u\ Nf + Rf$

$Td <= u\ Nd + Rd$

$Tt <= u\ Nt + Rt$